MICROSTRUCTURAL ANALYSIS OF POLYDEFORMED SCHISTS FROM THE SOUTHERN MARGIN OF THE PAN-AFRICAN ZAMBEZI BELT, AFRICA

A Thesis

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for the degree Bachelor of Science

by

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ABSTRACT

The Late Proterozoic, east-west trending Pan-African Zambezi belt in south-central Africa crosscuts the Middle Proterozoic, northeast trending Irumide orogenic belt. The southern Zambezi/Irumide margin contains Irumide 'basement complex' that was remobilized during Zambezi orogenesis. Schist units along the Ngonga River, Zambia, displayed no mesoscopic evidence of an older fabric to suggest that they were in fact remobilized 'basement complex', whereas one of the same lithologic units exposed along the Mutama River just to the east, did display an older, northeast trending structural fabric that had been overprinted by the east-west Zambezi fabrics. Microstructural analysis of the Ngonga samples of presumed Irumide age, however, did reveal evidence of an earlier, pre-Zambezi, tectonic fabric preserved within pre-Zambezi garnet porphyroblasts. The assignment of the schists to older 'basement' and younger 'cover' was thus established by this study. Detailed analysis of the timing of metamorphic mineral growth relative to the sequential stages of Zambezi deformation that affected both remobilized 'basement' and the 'cover' metasediments, was used to determine the progression of pressure and temperature conditions during deformation. These data were then used to develop a tectonic model for the southern margin of the Zambezi belt.

INTRODUCTION

TECTONIC SETTING OF STUDY AREA

The study area for this report is located along the southwestern margin of the east-west trending Pan-African Zambezi belt in south-central Africa (Fig.1). This Late Proterozoic (approx. 800 Ma, Hanson et al., 1988) belt crosscuts the northeast-southwest trending, Middle Proterozoic Irumide belt which has structural trends that parallel those of the Choma-Kaloma block to the southwest, both containing structures of Kibaran age (c.1350 Ma). This parallelism of structures of the same age between the Irumide and Choma-Kaloma block indicates that they represent a once continuous orogenic belt that was crosscut and overprinted by the Zambezi belt (Hanson et al.,1988a), possibly by ensialic-type tectonic processes or by rifting and subsequent collisional tectonics to produce the Zambezi orogenic belt (Daly,1986). The ensialic model is supported by the lack of displacement of the structural trends north and south of the Zambezi belt, whereas rifting and ocean basin development are suggested by theories invoking divergence and subsequent collision of the Congo and Kalahari cratons.

The southern margin of the Zambezi belt is marked by a broad zone of ductile shearing and is considered to represent the orogenic front, or southern limit of deformation associated with the Zambezi orogeny. Shear

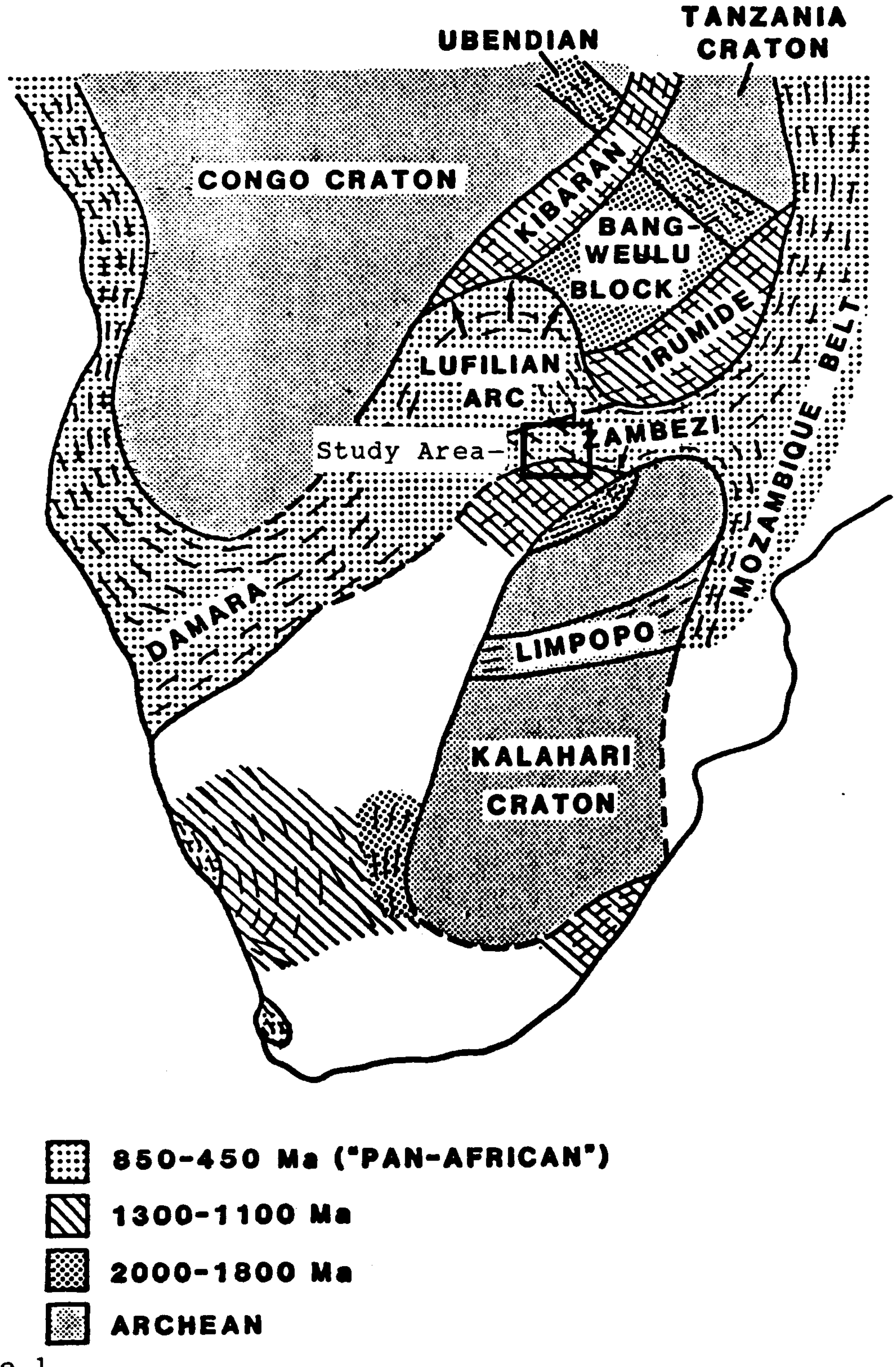


Figure 1.
Simplified map of southern and central Africa showing the distribution of cratons and mobile belts. Modified from Hunter and Pretorius (1981).

sense indicators within mylonites along this margin suggest north-over-south thrusting oblique to the east-west Zambezi strike, whereas mineral stretching lineations in orthogneisses within the Zambezi belt suggest slip parallel to strike. Together, a transpressive tectonic regime is inferred (Wilson et al.,1987)

The northern and southern margins of the belt both contain wide tracts of remobilized Middle Proterozoic (Kibaran) basement. The southern zone of remobilization is 30 km wide and contains lozenges of weakly overprinted units with Kibaran fabrics that are surrounded by units completely transposed into east-west trends during Zambezi deformation. Detailed studies of structurally remobilized basement within this zone are being undertaken in order to determine the kinematic history and progressive structural evolution of the southern orogenic front of the Zambezi belt (Hanson, Wilson, at present)

GEOLOGY OF THE STUDY AREA

EARLY STUDIES

Tavener-Smith (1961) was the first researcher to describe and map, in any detail, the units along the southwestern margin of the Zambezi belt. His study was primarily focused on what he interpreted to be stratigraphic relationships affected by granitisation processes, without recognition of the significance of the mylonitic structural fabrics in the area. He constructed a stratigraphic column based on what he interpreted to be bedding plane orientations that were actually foliation surfaces, and thus his regional geologic interpretations were somewhat lacking (de Swardt et al.,1964). Tavener-Smith mapped a single, regionally extensive schist unit termed the 'Chilumbwe Schist' and assigned a Middle-Late Proterozoic age to the unit based on lithologic correlation with the Katangan system occuring in northern Zambia. He described the unit as semipelitic and psammitic schists consisting of quartz-biotite-schist with lesser amounts of quartz-biotite-muscovite-schist and quartz-muscovite-schist, all of which contain garnet, kyanite or both. Tavener-Smith also described a thick "conglomeratic" unit which he interpreted as being sedimentary in origin. More recent research has lead to the interpretation of these conglomerates as tectonic conglomerates formed during Zambezi shearing (Brown, 1966; de Swardt et al., 1964; Wilson et al., 1985, 1987). Tavener-Smith believed that the Chilumbwe schist had been progressively transformed into acid gneisses toward the south by granitisation, and therefore assigned the sheared gneissic rocks along the Zambezi belt margin a younger age than the schist.

Brown (1966) recognized the presence of remobilized 'basement complex' of probable Middle Proterozoic age within the southern margin of the Zambezi belt. He included the sheared granitic gneisses and associated schists and quartzites into the Mutama Formation and assigned this unit to the older 'basement complex' based on his recognition of pre-Zambezi structural fabrics within these units, that had been refolded and intensely sheared during Zambezi deformation. Brown differentiated the older schists and gneisses from younger metasedimentary units that occur as infolds and fault slices within the remobilized basement complex and that appeared to lack older structural fabrics, and assigned these to the 'Katangan System' on lithologic grounds. He characterized the younger 'Katangan System' schists as typically fine grained, finely laminated schists composed of quartz and biotite with garnet and labeled the unit the Nteme Schist Formation. He mentioned the presence of mylonites and pegmatites but offered no regional interpretations. The tectonic conglomerates were identified as such without elaboration.

Brown described the Mutama Formation as consisting of quartz-biotite-muscovite-feldspar augen gneiss, quartz-muscovite schist, biotite schist, muscovite quartzite, sheared pegmatite and amphibolite, and tectonic conglomerates. The schists were interpreted to have been 'reconstituted' from the gneisses in the zones of most intense shearing. The quartzites were thought to be silicified blastomylonites. Brown recognized banding striking northeast in gneisses within the Mutama Formation that existed before the development of the west-northwest Zambezi foliation and therefore concluded that these rocks were older 'basement complex'.

de Swardt and Drysdall (1964) reinterpreted Tavener-Smiths data and were the first to recognize the occurrence of 'basement complex' along the Zambezi belt margins, and thus suggested that Pre-Katangan basement was remobilized and structurally transposed by Katangan (Zambezi) deformation. They characterized the Mutama units as consisting of biotite gneisses with subsidiary acid gneisses, quartz-feldspar granulites, and porphyroblastic gneisses and quartzites, all of which were intruded by basic igneous units. de Swardt and Drysdall's most significant contributions were to recognize the structural evidence for overprinted pre-Katangan basement units within the southern margin of the Zambezi belt, and to develop a more complete understanding of the progression of tectonic events that occurred there. They presented a new map of the area studied by Tavener-Smith and Brown, in which they subdivided the original Chilumbwe Schist of Tavener-Smith into an older, Kibaran unit that represented part of the 'basement complex' and a Chilumbwe Schist unit of more limited areal extent that they assigned to a younger, Katangan-equivalent age.

RECENT WORK

More detailed mapping along the southern margin of the Zambezi belt was conducted by Wilson and Hanson in 1986. They subdivided the gneissic rocks in the area into mylonitic and nonmylonitic varieties and further subdivided the Mutama Formation, as mapped by Brown (1966), into several distinct units dominated by schist (Figs.2,3). A schist unit exposed along the Mutama River was observed to contain an older structural fabric that had been refolded and crosscut by younger, west-northwest trending Zambezi foliations and was therefore interpreted to be a Kibaran metasedimentary unit that was remobilized during Zambezi orogenesis ('Kibaran Schist' unit, Fig.3). A second metasedimentary unit, informally termed 'schist-psammite', was seen to contain only the west-northwest Zambezi fabrics on outcrop, and therefore could not be assigned a pre-Zambezi age based on structural evidence observed in the field.

Both the 'Kibaran Schist' and 'schist-psammite' units were traced westward across an area of generally poor exposure to the Ngonga River,

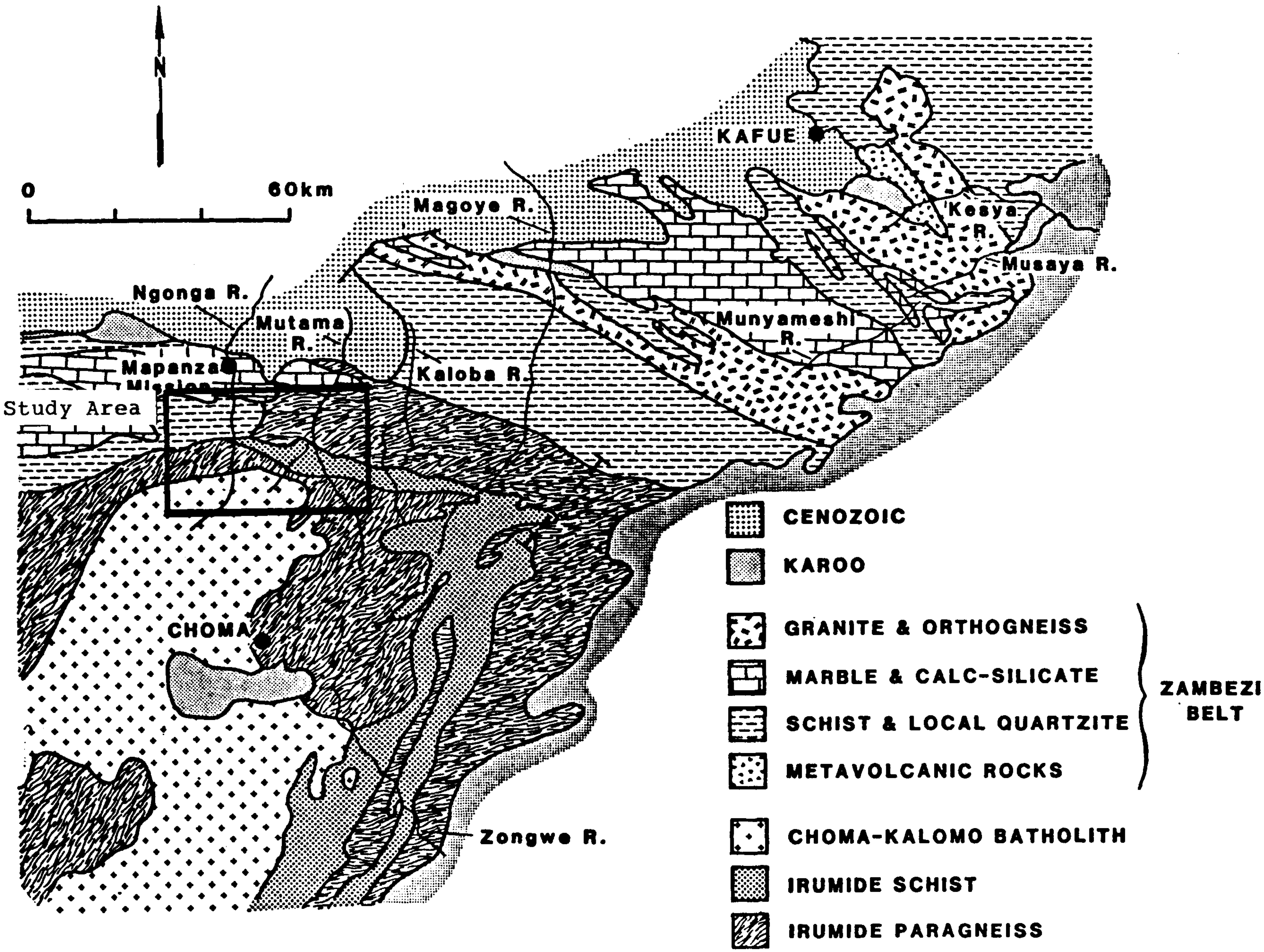


Figure 2. Geologic map of the Zambezi Belt in southern Zambia. From Hanson et al.(1988)

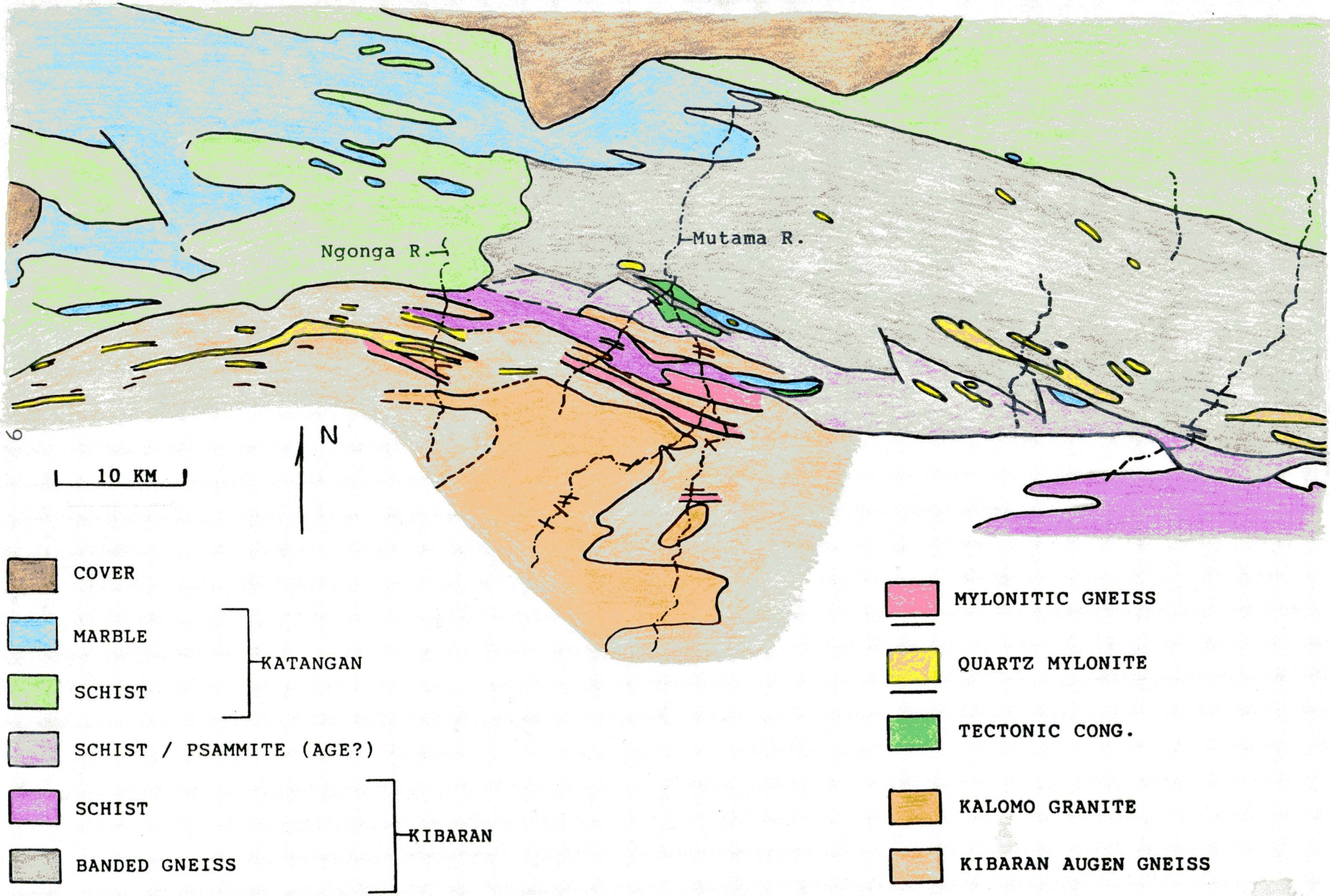


Figure 3. Geologic map of the study area.

where de Swardt and Drysdall (1964) had previously inferred the presence of a younger 'Katangan' schist unit (Chilumbwe Schist) and an older basement complex consisting of schists and gneisses. In the Ngonga area, the only mesoscopic structural fabrics observed on outcrop in these units had west-northwest trends and were interpreted to be of Zambezi age. The inferred correlation and ages of these units therefore must be tested in order to establish whether the assignment to the older 'basement complex' established in the Mutama River area can be applied to the Ngonga area.

Hanson and Wilson described the main structural fabric in all of the schist units in the Ngonga area as consisting of a compositional banding that parallels a penetrative schistosity, termed S1Z to signify the first Zambezi fabric. The parallelism of banding and foliation is good indication that a process termed transposition had occurred such that all previous mesoscopic fabrics in the rock were structurally and metamorphically 'erased' by isoclinal folding and shearing to form the existing structural fabric, even though no evidence for F1 isoclinal folding of the banding was observed on outcrop. In the case of the presumed Kibaran Schist, a pre-existing tectonic foliation associated with Irumide (Kibaran age) orogenesis must have been transposed into the west-northwest Zambezi trend. In the younger Chilumbwe Schist, which was first deformed during the Zambezi orogeny, transposition of original sedimentary bedding must have occurred. In strongly transposed rocks such as these schists, the evidence for older structural fabrics is commonly preserved only in metamorphic porphyroblasts and, therefore, must be microstructurally analyzed so that transposed tectonic banding can be differentiated from transposed bedding.

Hanson and Wilson also described a pervasive crenulation cleavage within all the schists along the Ngonga traverse and termed this fabric S2Z to designate the second Zambezi fabric. The S2Z crenulation cleavage is commonly axial planar to folds that affect the composite S1Z banding-schistosity.

OBJECTIVES OF THIS STUDY

The focus of this study was 1) to distinguish, through microstructural analysis, Zambezi belt schists that represent polydeformed Mutama 'basement' from Chilumbwe Schist 'cover' deformed only during the Zambezi orogeny, based on the presence or absence of earlier structural fabrics preserved within porphyroblasts; 2) to identify relations between deformation and metamorphism through the analysis of mineral growth orientations relative to structural fabrics so that single or multiple metamorphic events can be characterized and synchroneity between these metamorphic events and deformation events can be deduced; and 3) to evaluate the progression of pressure and temperature (P-T) parameters through time based on metamorphic assemblages associated with each regional metamorphic event.

METHODOLOGY

SAMPLE PREPARATION

Rock samples discussed in this report were collected along the Ngonga River, Zambia in two separate field seasons. At the time of hand sample collection, the orientations of all recognizable structural features such as schistosity, axial planar foliations, crenulation cleavages, crenulation lineations, mineral lineations, compositional banding, fold hinge lines and axial surfaces, and any other pertinent structural trends in the area were recorded. The strike and dip of foliation planes were marked, if possible, by a horizontal line with an arrow in the direction of strike and a tick mark indicating the down-dip direction (Fig. 4). Mineral lineations and fold hinges were marked by lines parallel to their trends with arrows indicating the direction of plunge. In many cases, foliation planes were oriented obliquely to any of the sample faces and thus could not be marked by lines of strike. In this case, strike and dip of one of the rock faces was marked, as above, so that the orientation of the sample in space could still be deduced in the lab.

Once in the lab, slabs of each sample were cut and thin sections were prepared in specific orientations with respect to the structural fabrics. Samples lacking a crenulation cleavage fabric were cut perpendicular to the primary foliation (S1) and parallel to the mineral lineation on the foliation planes and were labeled 'a' sections. The remaining samples were cut perpendicular to the crenulation cleavage planes and perpendicular to the crenulation lineation direction, and were labeled 'e'

MARKING ORIENTED HAND SAMPLES

Orientation of all foliations, lineations, fold axes + axial planes, etc. must be carefully measured on the outcrop where specimen is collected and clearly marked on sample where appropriate.

CUTTING AND MARKING 3 ⊥ ORIENTED THIN SECTIONS

1. Cut oriented slices A, B, C
2. Cut oriented chips A, B, C
3. Cut notches in each chip to mark orientation.

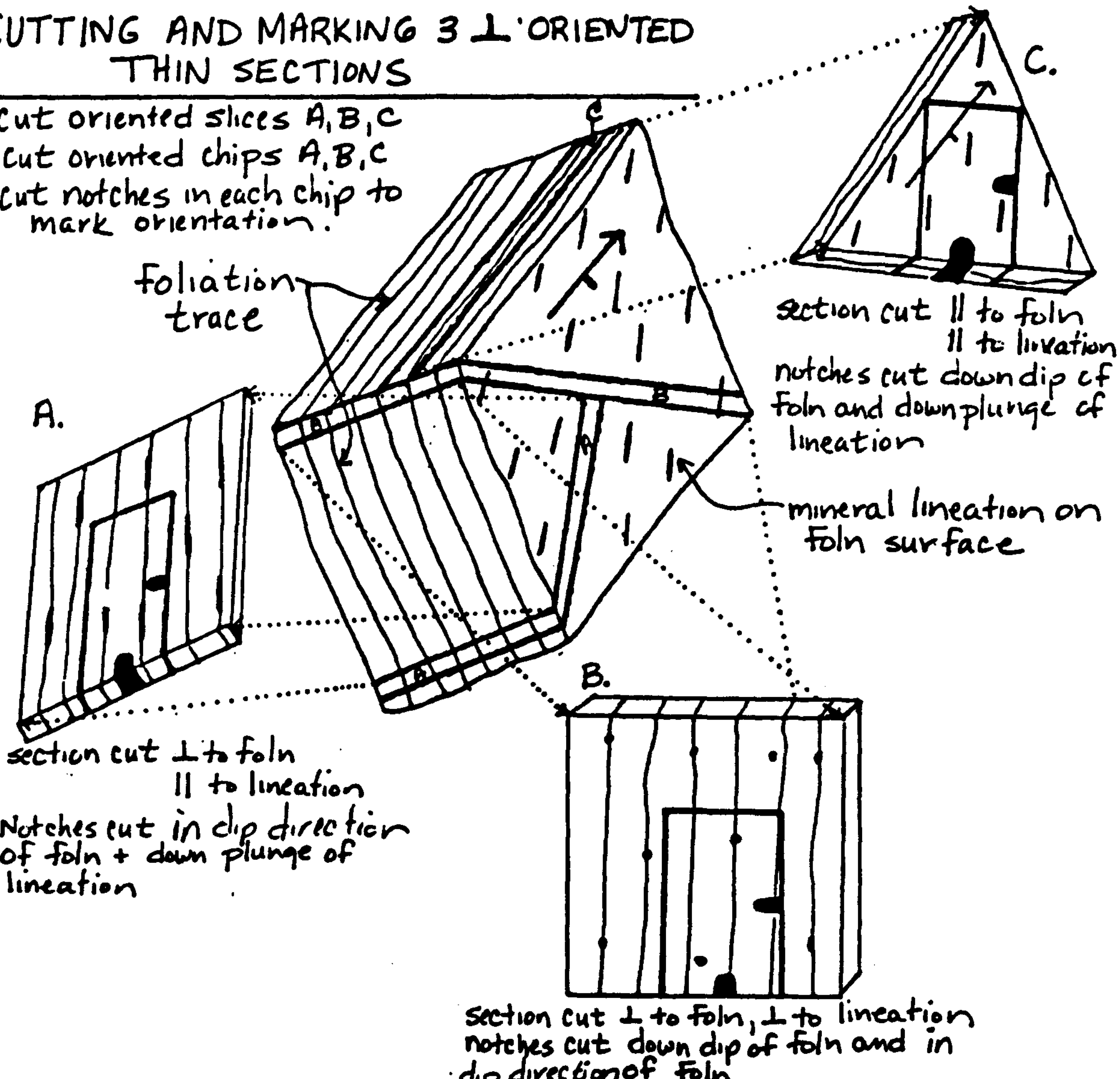


Figure 4. **a) Technique used to orient hand samples in the field.**
b) Orientation of "a", "b", & "c" samples.

sections. In the a-sections, notches were cut in the dip direction of the foliation and in the down-plunge direction of the lineation. In the e-sections, notches were cut down-dip of the foliation and in the dip direction of the foliation. Once under the microscope, the notches allow for an understanding of microstructural orientations so that they can be related to mesoscopic and regional fabric orientations within the study area.

PRINCIPLES OF MICROSTRUCTURAL ANALYSIS

Metamorphism of a rock body of a given composition will produce characteristic mineral assemblages that are directly related to the ambient temperature and pressure parameters. When regional metamorphism is accompanied by a deformation event, minerals nucleate and grow in preferential orientations controlled by the principal strain directions. Analysis of the minerals that define the resultant structural fabric can therefore offer insight into the pressure and temperature (P-T) conditions during regional deformation events.

Polydeformed and metamorphosed rocks typically display structural fabrics from more than one of the these events. In these cases, the earliest fabrics can be distinguished from the later fabrics by overprinting relationships, similar to the way in which one would realize that a fence offset by a fault must have been present before the displacement occurred (Fig. 5). Porphyroblast-bearing rocks may have structural fabrics included within the porhyroblasts (Si) that may or may not be related to the external fabrics within the matrix (Se). The

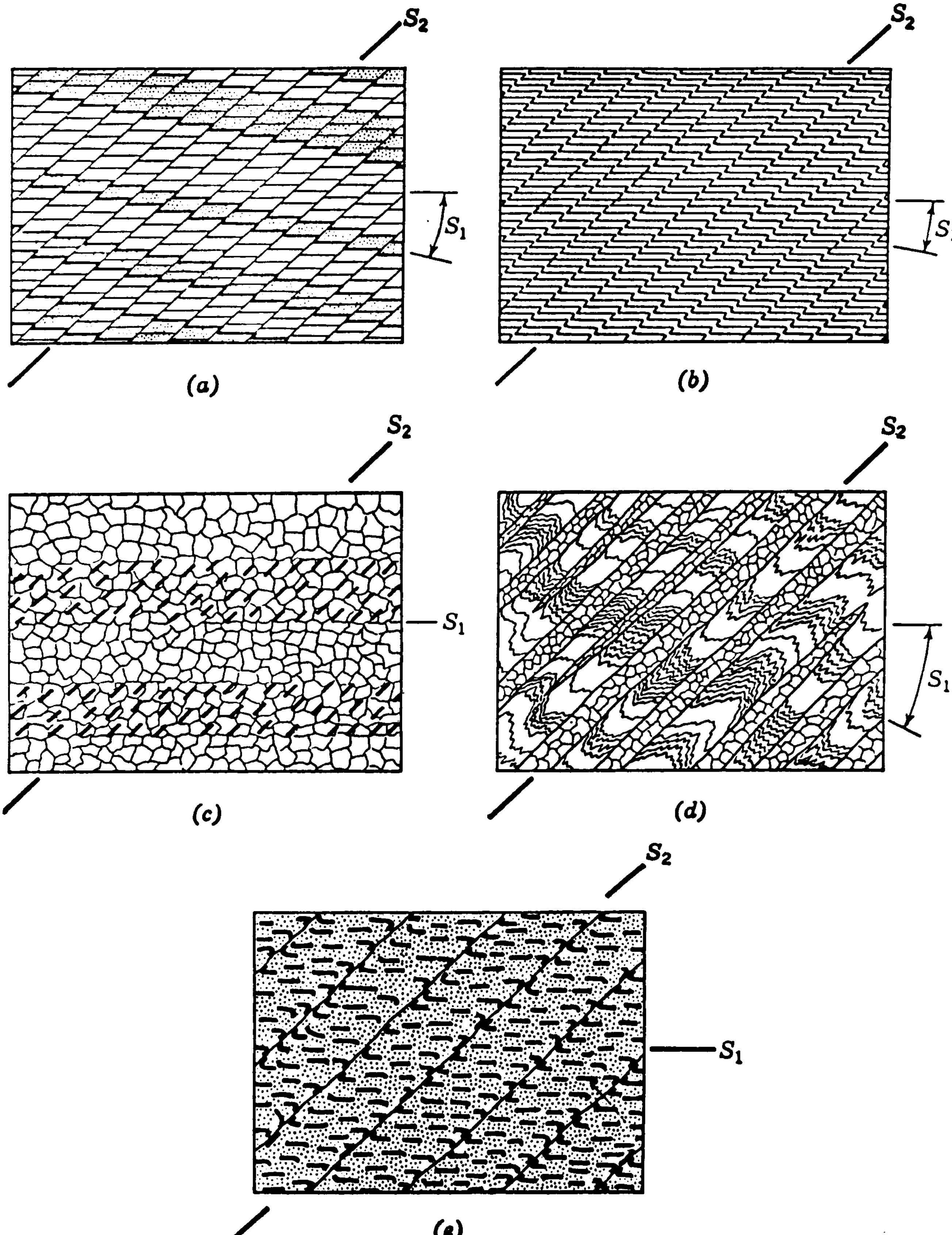


Figure 5. **Age relations between foliations: S_2 is later than S_1.** (From Turner et al., 1963)

presence of Si fabrics in porphyroblasts oriented obliquely to Se fabrics in the matrix represents strong evidence for polydeformation, even in the absence of mesoscopic overprinting relations.

The designation of successive foliations within a rock begins with the identification of the earliest formed foliation. If the original bedding planes can be identified, they are designated S0 and considered to be the "initial" fabric. The first deformation-induced foliation is designated S1 and all successive foliations (S2, S3...etc.) are identified by overprinting relations. In rocks, these overprinting relations may exist as (Fig. 6): A) Si preserved within a porphyroblast that is bounded by a fabric, Se, oriented obliquely to Si; B) new domains of micas cutting an older foliation; C) replacement or successive rim growth of one metamorphic mineral by a mineral phase characteristic of a different metamorphic grade; D) crenulation foliation truncating and deforming an older foliation (Fig. 6).

The presence of porphyroblasts, and their ages relative to the surrounding fabrics, then, can offer information about the metamorphic grade associated with different deformation events (Fig. 7a). The chemistry of porphyroblasts such as garnet can reveal detailed signatures of the P-T conditions responsible for their formation which, when combined with relative age data, can be a very useful tool in deciphering P-T progressions in polymetamorphosed rocks. Determination of relative age relationships between porphyroblasts and the surrounding fabric is an attempt to understand if the porphyroblast formed before, during, or after the event that formed the fabric. There are distinct

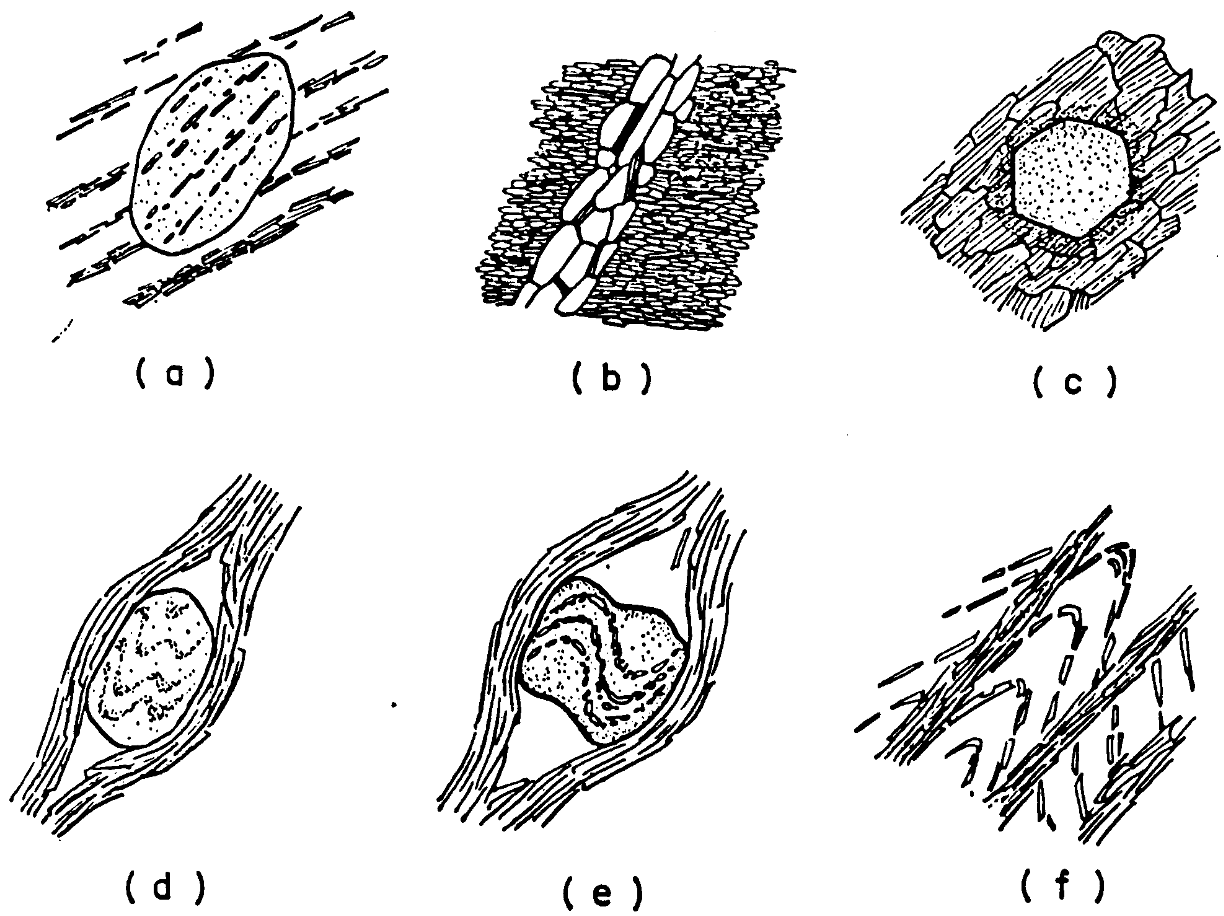
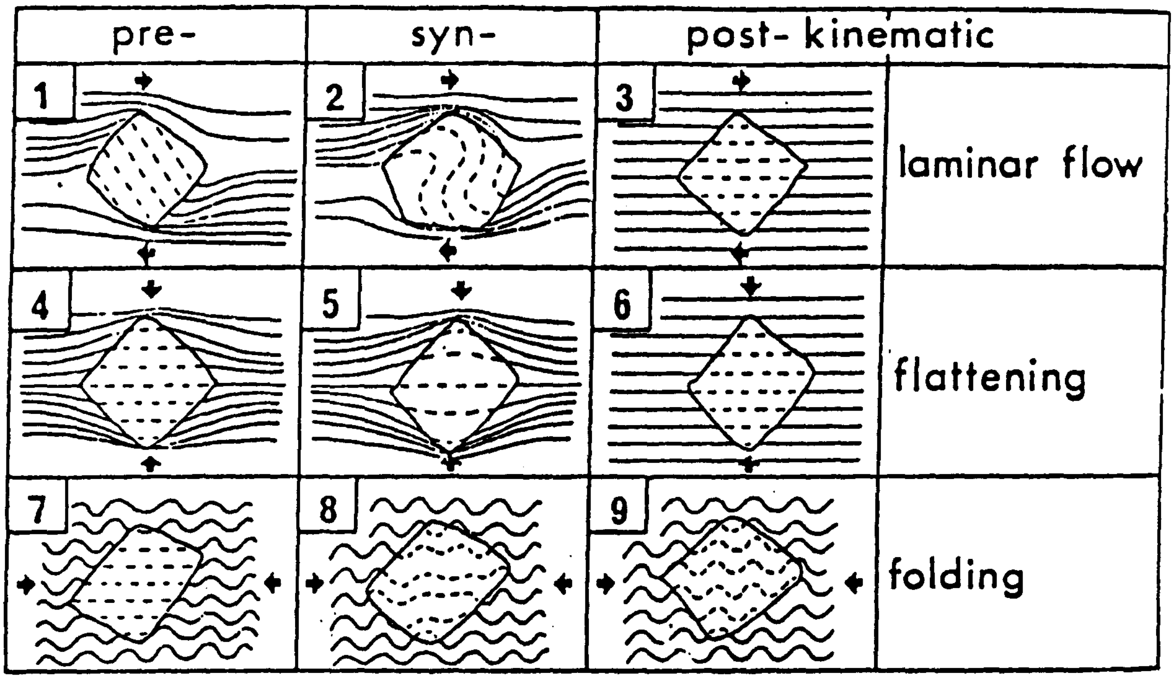


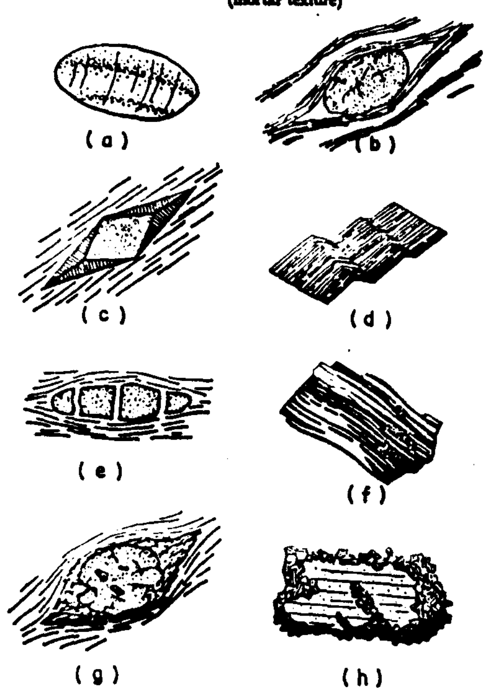
Figure 6. Characteristic relations in polymetamorphic rocks. (a) Helicitic crystal, S_i discordant with S_e. (b) Layer of coarse micas cutting a fine foliation. (c) Blue-green coloration in actinolite in a rim around garnet. The actinolite formed after the garnet and derived certain constituents from it. (d) Helicitic crystal enclosing folded S-surface wrapped around by a later foliation. (e) Snowball garnet with S_1 as rotational S_i wrapped around by S_2. (f) Older folded foliation S_1 cut by planar S_2 (From Spry, 1969)

A)

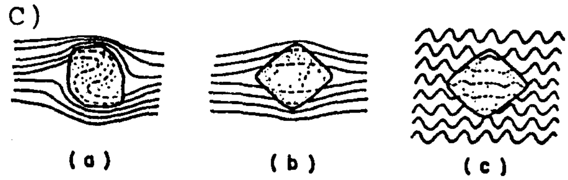


The "eight diagnostic forms" of porphyroblast/matrix relationships, reproduced from ZWART (1962, Fig. 1).

B) Characteristics of pre-tectonic crystals. (a) Undulose extinction and deformation lamellae in quartz. (b) Cracked garnet wrapped around by the foliation. (c) Pressure fringes around pyrite. (d) Kinked biotite. (e) Fragmented garnet. (f) Plagioclase with deformation twins. (g) Garnet with a sheath of chlorite along the foliation. (h) Large amphibole crystal breaking down to an aggregate of small crystals (mortar texture)

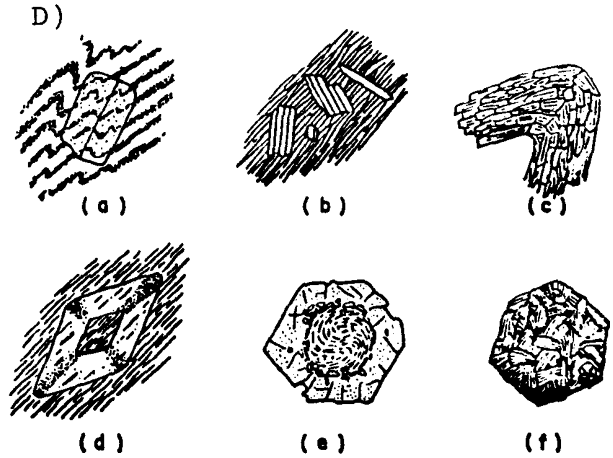


C)



Characteristics of syntectonic crystals. (a) Snowball garnet. (b) Andalusite porphyroblast which grew during flattening of a pre-existing foliation. (c) Porphyroblast which grew during the crumpling of a pre-existing foliation (b and c after Zwart, 1961, 1963)

D)



Characteristics of post-tectonic crystals. (a) Helicite structure in albite, S_i (*S*-surface within the crystal) concordant with S_e (*S*-surface outside of the crystal). (b) Cross-micas. (c) Polygonized micas in a fold. (d) Chiastolite with central helicitic and outer cross structure and boundaries discordant with the foliation. (e) Garnet with syntectonic rotational core and post-tectonic idioblastic rim. (f) Random aggregate of chlorite as a multi-crystal pseudomorph after garnet

Figure 7. Pre-, syn- and post-tectonic porphyroblasts.
(From Spry, 1969)

porphyroblast-external fabric relations that can be used to establish pretectonic, syntectonic or post- tectonic crystal growth (Fig. 7b,c,d). Pretectonic porphyroblasts 1) are commonly wrapped by Se; 2) may have pressure shadows that parallel Se; 3) commonly have inclusion trails (Si) that are straight and oblique to Se; 4) may have randomly oriented inclusions with foliated Se. Syntectonic porphyroblasts may show 1) Si that is more tightly microfolded towards the margins of the porphyroblasts with Se even more tightly microfolded; 2) Si continuous with Se but progressively more deflected near the porphyroblast margins; 3) Si that is sigmoidally curved and continuous with Se due to porphyoblast growth during transposition of Se. Post-tectonic porphroblasts commonly display 1) Helicitic texture, that is, Si is continuous with Se with both fabrics being straight or identically folded; 2) random arrangement with respect to Se; 3) Se that is truncated by the porphyroblast, without any deflection of Se, indicating replacement of associated Se minerals by the porphyroblast.

In strongly deformed polymetamorphic rocks, early foliations may be completely 'erased' by later fabrics, a process known as transposition. Rocks containing an initial foliation that is deformed, for example, to produce isoclinal folds, will often lose most or all evidence of the fold closures, leaving what seems to be a single foliation representing one metamorphic event. This process forms what is called a "transposition foliation". Porphyroblast-bearing rocks with a transposed earlier fabric may contain no detectable fold closures or evidence of earlier fabric when observed in hand sample, but may reveal inclusion trails of relict fabrics within pre- or syntectonic porphyroblasts , when viewed in oriented thin sections (Fig.7a,b,c). These included porhyroblasts may be the only evidence of transposition.

MICROSTRUCTURAL ANALYSIS

NGONGA SAMPLES

The Ngonga samples studied will be discussed in order from north to south along the Ngonga River traverse across Zambezi strike (Fig. 3). Eleven schist samples from ten different locations were collected and analyzed (Fig. 8). Table 1 summarizes the timing of mineral growth with respect to each structural fabric, as described in the following discussion.

4-175-e Semipelitic mica-quartz schist:

This sample is dominated by a main S1Z schistosity and displays a pervasive, fine, S2Z crenulation lineation on the S1Z surfaces in hand sample only. S1Z is defined by compositional banding of mica-rich and quartz-rich domains (Plate 1). The mica-rich or 'M' domains show dimensional alignment of muscovite and biotite parallel to S1Z indicating syn-S1Z growth. The quartz-rich or 'Q' domains contain quartz, feldspar and less abundant muscovite and biotite with slight elongation of quartz and feldspar along S1Z. Accessory subhedral garnet is present and shows no clear inclusion patterns or core-rim character, forms 120 triple points with quartz and feldspar, and is intergrown with muscovite and biotite laths, therefore, it is considered to be syn-S1Z. The feldspar is considered to be pre-S1Z due to slight wrapping of S1Z around many feldspar grains. In thin section, S2Z is defined by slight open folding of M-domains with no observable crystal growth convincingly associated

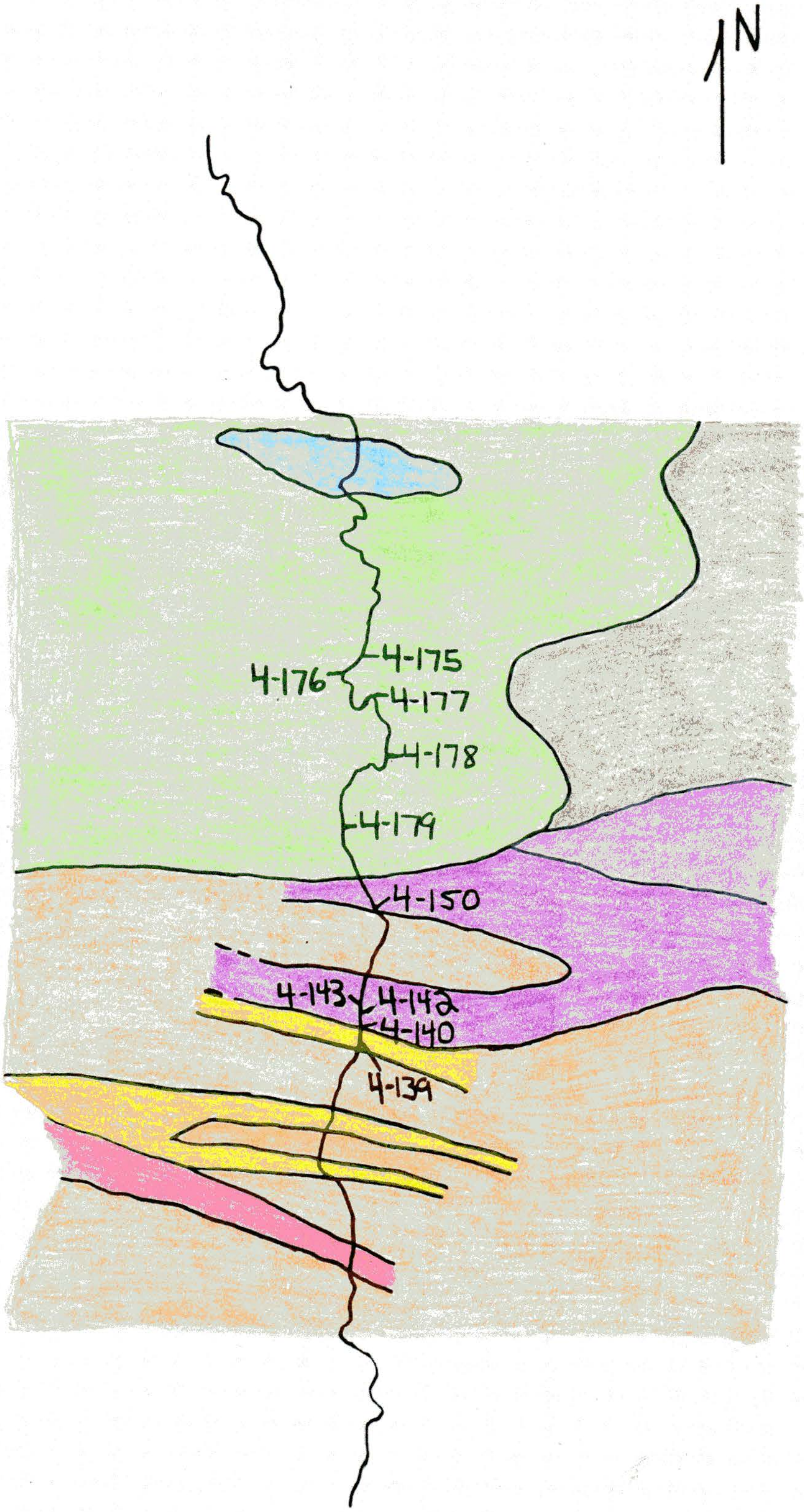


Figure 8. Geologic map of the Ngonga River traverse.
Sample localites marked. Legend from Fig. 3 applies.

Key
●- Timing definite
0- Timing uncertain
i- Inclusions in porphyroblast
E- Early
L- Late

		SI			S1Z			S2Z	
		PRE	SYN	POST	PRE	SYN	POST	SYN	POST
4-175-e	Quartz					●			
	Muscovite					●		0	0
	Biotite					●			
	Feldspar				●				
	Garnet					●			
4-176-a	Quartz					●			
	Muscovite					●+L	0		
	Biotite					●			
	Feldspar				●				
4-177-e	Quartz					●			
	Muscovite					●		●	
	Biotite					●		●	
	Feldspar					●	0		
	Staurolite					●	0		
4-178-e	Quartz					●			
	Muscovite					●			●
	Biotite					●			
	Kyanite						●		
	Garnet					0L	0		
	Feldspar					0L	0		
4-179-e	Quartz					●			
	Muscovite					●		0	
	Biotite					●		0	
	Feldspar				●	●			
		PRE	SYN	POST	PRE	SYN	POST	SYN	POST

Table I. Timing of mineral growth relative to the to the formation of tectonic fabrics.
(continued on next page)

		SI			S1Z			S2Z	
		PRE	SYN	POST	PRE	SYN	POST	SYN	POST
4-150-e	Quartz		●i			●			
	Muscovite					●		●	
	Biotite					●		●	
	Garnet		●	●					
	Feldspar				0	0			
4-143-e	Quartz					●			
	Muscovite				●	●			
	Biotite					●			
	Garnet				0	0E			
4-142be	Quartz		●i			●			
	Muscovite					●		●	
	Biotite					●		●	
	Garnet		●	●					
	Feldspar				●				
4-142-e	Quartz		●i			●			
	Muscovite					●		●	
	Biotite					●		●	
	Garnet		●	●					
4-140-e	Quartz					●			
	Muscovite					●		●	
	Biotite					●		●	
	Staurolite						0	0	
	Garnet							●E	0
		PRE	SYN	POST	PRE	SYN	POST	SYN	POST

		SI			S1Z			S2Z	
		PRE	SYN	POST	PRE	SYN	POST	SYN	POST
4-139-e	Quartz					●			
	Muscovite				●	●			
	Feldspar				●				

Table I. (continued)

with S2Z. There are, however, a few laths of muscovite oriented obliquely to S1Z (Plate 1a) that show a slight hint of systematic orientation to the S2Z microfolds but could also be considered randomly oriented. These mucovites are considered to be syn to post S2Z.

4-176-a Finegrained micaceous-feldspathic quartzite:

This sample displays a single S1Z foliation both in hand specimen and in thin section and contains an L1Z mineral lineation on S1Z that is only detectable on mesoscopic scale. S1Z is defined by dimensional alignment of quartz and mica with quartz constituting 80-90% of the whole rock composition (Plate 2). Pre-S1Z feldspar occurs as augen wrapped by S1Z foliations. Helicitic muscovite occurs containing quartz inclusions (Si) oriented parallel to S1Z in the matrix. These muscovites are somewhat elongate parallel to S1Z and are therefore considered to be late-S1Z.

4-177-e Crenulated quartz-muscovite-biotite-staurolite schist:

S1Z schistosity and S2Z crenulation cleavage are both well developed within this sample with no evidence of any earlier fabric. S1Z is is defined by Q-domains of quartz, feldspar and micas preserved as microlithons within the walls of S2Z M-domains (Plate 3). The Q-domains show individual grains of quartz and feldspar elongate parallel to S1Z. Though the feldspar grains are generally elongate parallel to S1Z, there are a few grains that appear to have overgrown S1Z, therefore, the feldspar is likely late-syn to post S1Z. Quartz and mica within the Q-domains are finely interbanded suggesting growth syn-S1Z. The

Q-domains also contain laths of muscovite and biotite oriented parallel to S2Z suggesting syn-S2Z growth. Subhedral staurolite occurs as elongate grains with long axes oriented parallel to S1Z. Quartz inclusion trails within the staurolites are parallel to S1Z and smaller than the grain size of quartz within the matrix, suggesting that the staurolite grew early-S1Z before the quartz in the matrix grew larger during the first stage of Zambezi deformation. It is possible, though, that if the staurolite growth was compositionally controlled by the S1Z fabric, the staurolite may have grown late to post S1Z with the increase of quartz grain size in the matrix occurring syn-S2Z. S2Z is defined by M-domains of muscovite and biotite. These M-domains are composed of limbs of microfolded S1Z micas rotated parallel to S2Z and of dimensionally aligned micas that grew syn-S2Z. There is no evidence of a pre-S1Z tectonic fabric.

4-178-e Crenulated quartz-muscovite-biotite-feldspar-kyanite-garnet schist:

This sample contains a dominant S1Z schistosity that is microfolded by S2Z crenulations. S1Z is defined by interbanded, closely spaced Q and M- domains (Plate 4). The Q-domains contain quartz and feldspar with small, prominent, 'ribbon' aggregates of coarser-grained quartz. The feldspars are generally elongate parallel to S1Z and contain inclusion trails that appear to be straight and continuous with S1Z in the matrix and are therefore considered to be late to post S1Z. The garnets are elongate parallel to S1Z and contain Si of quartz and opaques that are straight and continuous with S1Z (Plate 4c,d), thus are considered to be either late S1Z or helicitic over S1Z. Kyanite occurs as randomly oriented subhedral porphyroblasts containing straight Si inclusions of quartz that are continuous with S1Z in the matrix (Plate 4a,b) and is therefore considered to be post S1Z. The presence and apparent timing of the kyanite may indicate heating post S1Z and pre-S2Z. S2Z is defined by microfolding of S1Z with differentiation of quartz out of the steep asymetric limbs of the microfolds leaving only muscovite and biotite. There appears to be little or no new crystal growth of muscovite or biotite associated with S2Z. Randomly oriented, blocky laths of muscovite occur containing curved Si microfolds that are continuous with microfolded S1Z and are therefore post S2Z.

4-179-e Crenulated quartz-muscovite-biotite-feldspar schist:

This sample contains S1Z schistosity crenulated by S2Z. S1Z is defined by dimensionally aligned quartz, muscovite and biotite. Feldspar occurs as pre-S1Z augen that have been wrapped and dynamically recrystallized during S1Z formation (Plate 5). S2Z is characterized by dimensionally aligned muscovite and biotite that grew parallel to the axial plane of the S2Z microfolds.

4-150-e Muscovite-biotite-quartz-garnet schist:

This section contains an S1Z schistosity crenulated by S2Z. S1Z is defined by compositional banding of quartz and mica with dimensional alignment of the micas parallel to S1Z. The fact that this banding parallels the S1Z foliation planes suggests that the banding may be related to a pre-S1Z fabric that was transposed by S1Z. S2Z is defined by pervasive crenulation of the S1Z mica domains with new mica growth parallel to the microfold axial planes. Microlithons between the S2Z crenulation cleavage domains preserve the S1Z fabrics and contain garnets. Plagioclase feldspar occurs within the microlithons with some grains wrapped by S1Z micas and cracked (pre-S1Z?) and other grains containing possible inclusion trails (cracks?) continuous with S1Z (syn-S1Z?). The garnets show three to four growth stages defined by inclusion-rich and inclusion-poor core zones and by rim zones which contain concentric inclusion trails of opaques and quartz that are separated from the inner zones by distinct dusty bands (Plate 6a). The occurrence of inclusion-rich and inclusion-poor zones indicates that the garnets must have grown over the external tectonic fabric at different rates, with the zones of abundant inclusions representing rapid growth. The garnet porphyroblasts appear to have grown entirely pre-S1Z, as evidenced by 1) qtz inclusion trails oriented obliquely to S1Z at different angles in each porphyroblast, therefore eliminating the possibility that the garnets grew early S1Z with S1Z subsequently rotated in the matrix as outlined by Bell (1985); 2) pressure shadows of quartz tailing away from the garnet porphyroblasts parallel to S1Z, and microfolded by S2Z (Plate 6a,b); 3) apparent dissolution flattening of some garnet porphyroblasts parallel to S1Z; 4) completely throughgoing extensional cracks cutting each garnet perpendicularly to S1Z. The inclusion trails in the garnets are considered to represent an earlier fabric (Sl-Irumide) that was transposed by the first stage of Zambezi deformation into S1Z, which therefore suggests that this schist unit represents remobilized Kibaran 'basement complex'.

4-143-e Quartz-mica-garnet mylonite:

This sample contains a single S1Z fabric. This fabric is defined by quartz and micaceous laminae with dimensional alignment of both quartz and mica parallel to S1Z (Plate 7a,b,c). Asymmetric augen or 'fish' of muscovite are observed that are wrapped by S1Z, are larger than S1Z micas, have tails that are drawn into S1Z, and have internal 'kinks', all of which suggests that they are of pre-S1Z age. Garnets occur as individual grains that are either equant or elongate parallel to S1Z, with the exception of at least one grain that is at right angles to S1Z. These garnets are cracked perpendicularly to S1Z suggesting pre-S1Z age. Augen-shaped aggregates of garnet also occur that are elongate parallel to, and wrapped by, S1Z which supports a pre-S1Z age. It is unclear whether these aggregates are fragments of once larger crystals or if the smaller grains grew as individual porphyroblasts. The former is supported by the S1Z wrapping of the augen and by what appear to be 'tails' of garnets trailing away from the aggregates parallel to S1Z. The latter is supported by the subhedral, equant shapes of many of the small garnets suggesting individual growth rather than fragmentation of a larger crystal. The possibility that the garnets may have grown syn-S1Z is supported by opaque inclusion trails that are continuous through the garnet aggregates and parallel to S1Z. The combination of both pre- and syntectonic criterion suggests that the garnets are possibly early syntectonic but does not rule out pre-S1Z formation.

4-142b-e1+2 Crenulated psammite:

These two samples are composed of quartz, muscovite, biotite and garnet and contain crenulated S1Z folia. S1Z is defined by dimensional alignment of mica and quartz and is crenulated by S2Z. S2Z crystal growth of muscovite and biotite is evidenced by dimensional alignment parallel to the axial planes of the S2Z microfolds. Zoned garnets occur displaying three to four growth stages based on the same criteria discussed for sample 4-150. Inclusion trail orientations and the presence of throughgoing cracks as discussed above suggest that these garnets are syn and post SI relicts and that this sample is remobilized Kibaran basement complex.

4-142-e Crenulated garnet-muscovite-biotite-quartz schist:

This sample is very mica and garnet-rich with S1Z pervasively crenulated by S2Z microfolds. S1Z is preserved mainly within the limbs of the microfolds and is dominated by micas that are dimensionally aligned within each limb and defined S1Z before the formation of S2Z (Plate 8). Quartz occurs as probable S1Z pressure shadows around many garnet porphyroblasts, but is too strongly folded by S2Z to definitely determine an orientation associated with the S1Z fabric. S2Z is defined by intense microfolding of the micas and by dimensionally aligned domains of muscovite and biotite that grew syn-S2Z. The garnets in this sample are very similar to those in sample 4-150 and are much more abundant. Each garnet displays multiple growth stages (3-5) as defined in the 4-150 discussion, with 'dusty' bands and zones that are more inclusion-rich than others as in 4-150. Inclusion rich cores appear to contain mostly straight trails of quartz when viewed under plane light and crossed polars, whereas curved trails can be imagined when the gypsum plate is inserted, but are too small to be established with certainty. There is no apparent preferred orientation of the inclusion trails from garnet to garnet which suggests that the garnets are pre-S1Z as discussed for 4-150. Cracks cut each garnet completely with the cracks oriented roughly parallel to S2Z, thus the garnets are considered to have cracked due to internal extensional stresses induced by S1Z compression, which supports a pre-S1Z garnet origin. The garnet inclusions are therefore considered to preserve SI fabric indicating that this rock is transposed basement complex.

4-140-e Quartz-biotite-muscovite-garnet-staurolite-schist:

S1Z and S2Z fabrics are preserved within this sample. S1Z is defined by finely interbanded quartz and mica lamellae, with dimensional alignment of the micas parallel to S1Z (Plate 9). Staurolite occurs as very elongate porphyroblasts with long axes parallel to S1Z, and contains inclusion trails of quartz that are continuous with S1Z. Many of the inclusion trails are curved where the margins of the staurolites are curved and straight where the margins are straight, suggesting that the staurolite grew post S1Z and pre- or early S2Z. Garnets were observed having inclusion rich cores with curved quartz trails and euhedral 'winged' rims that lacked inclusions. The curved inclusion trails are not as tightly folded as Se which suggests that the garnet cores grew early S2Z. The euhedral rims appear to have grown preferentially along mica-rich bands and at a slower rate than the cores, which prevented the 'trapping' of inclusions. These rims, then, may represent post S2Z growth.

Because this sample comes from the same unit as those containing microstructural evidence of older fabrics in porphyroblasts, and is one of the southernmost samples collected along the southwestern Zambezi margin, it would be expected to contain pre-S1Z fabrics. The presence of garnet indicates that the bulk rock composition could have supported early garnet growth assuming that the composition was more or less constant. This sample was collected adjacent to a mylonitic zone immediately to the south. It is possible that the increased flow of metamorphic fluids associated with the mylonites may have induced retrograde metamorphic processes to break down any existing garnets during D1Z mylonitisation.

4-139 Quartz mylonite:

This sample displays a dominant S1Z mylonitic foliation. C-mylonitic planes are defined by quartz strings and dimensionally aligned muscovite. S-mylonitic planes can be inferred in quartz sub-grains. Pre-tectonic feldspar and muscovite occur that are wrapped by S1Z-C (PLate 10).

S1Z S1Z

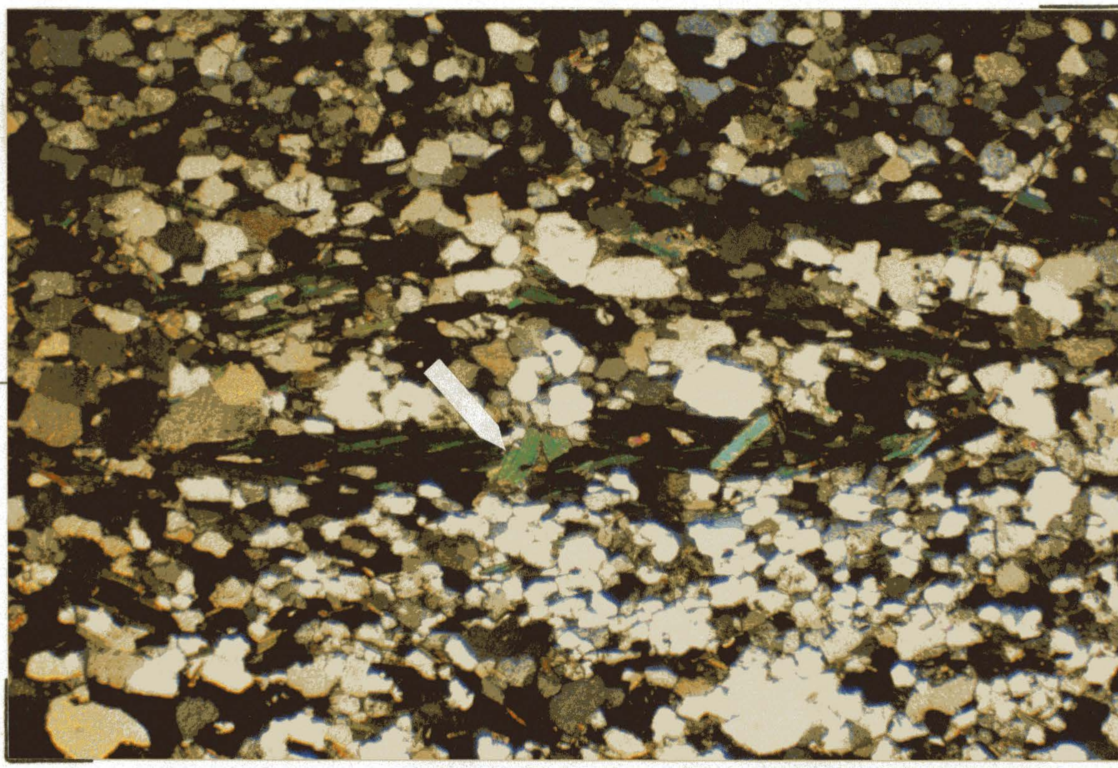


Plate 1a. Sample 4-175-e, crossed polars. Arrow marks post-S1Z muscovite.

S1Z S1Z

Plate 1b. Sample 4-175-e, crossed polars. Arrows mark 1) feldspar augen wrapped by S1Z;2) post-S1Z muscovite.

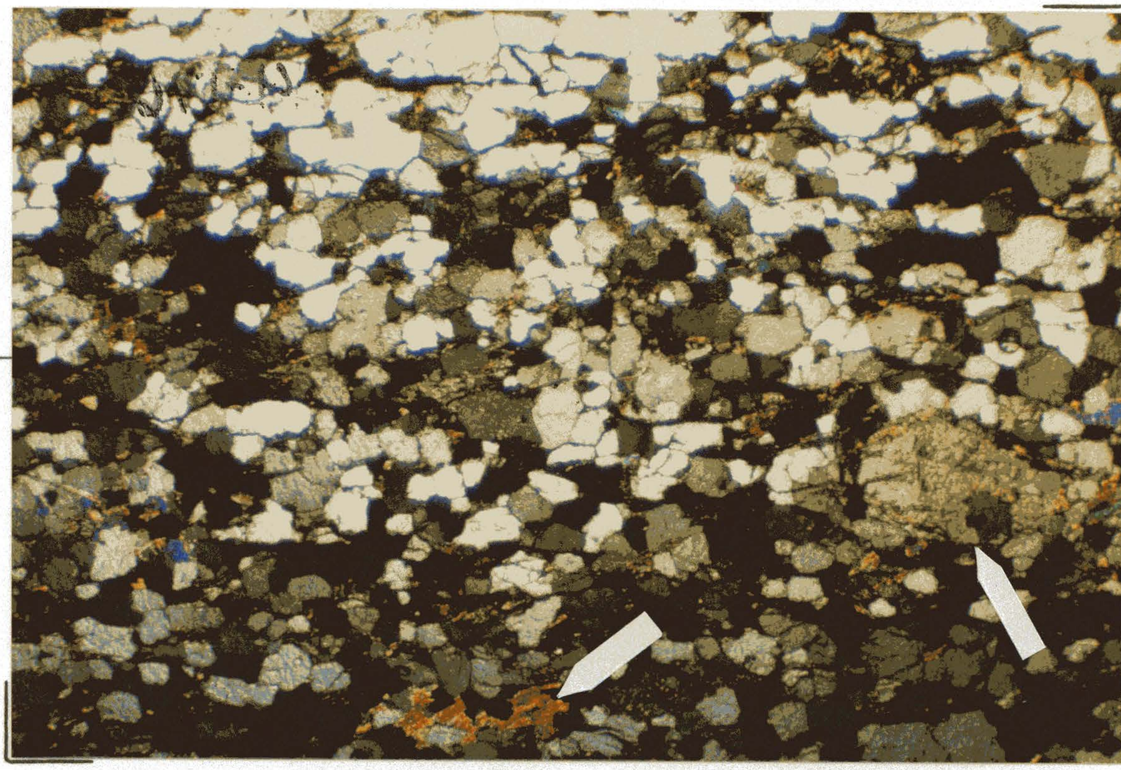


Plate 2. Sample 4-176-a, crossed polars. Arrows mark 1) probable post-S1Z muscovite; 2) wrapped feldspar augen.

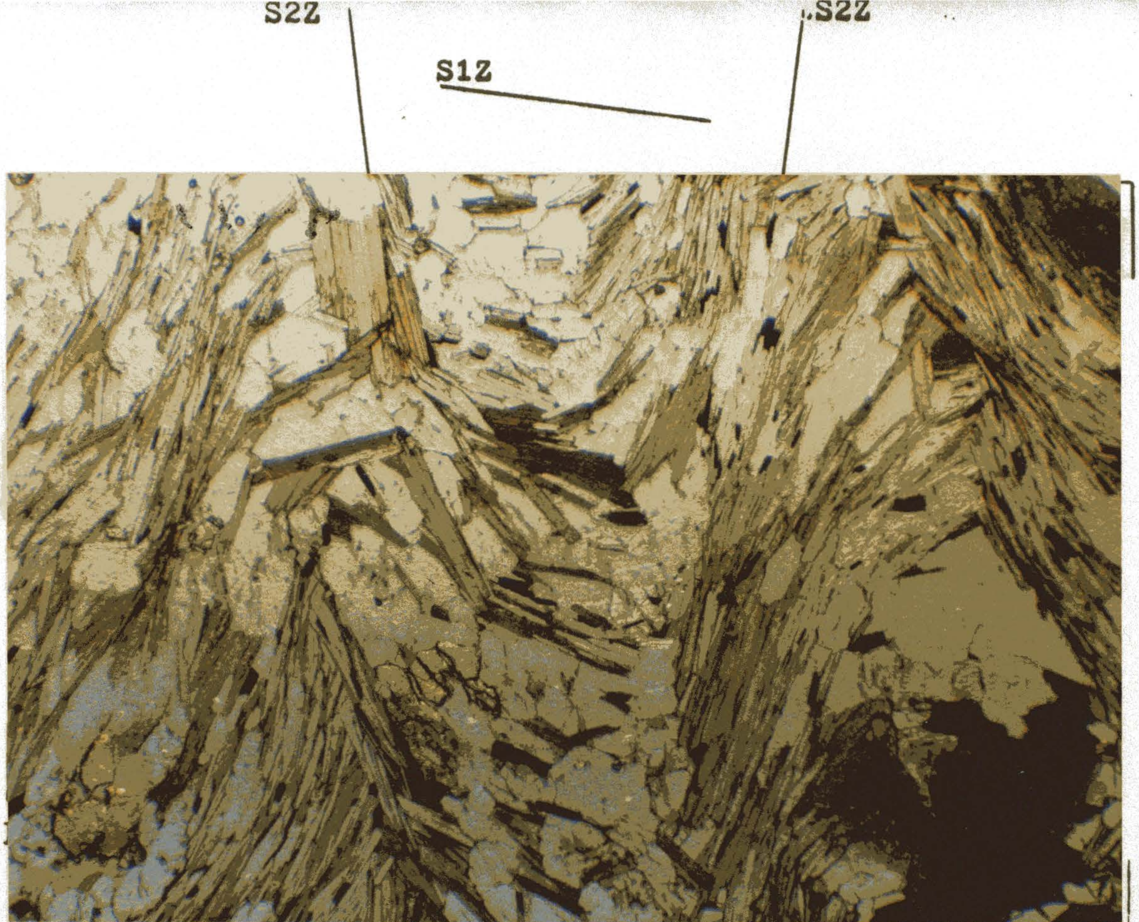


Plate 3a. Sample 4-177-e, plane light. S1Z Q-domains and S2Z M-domains.

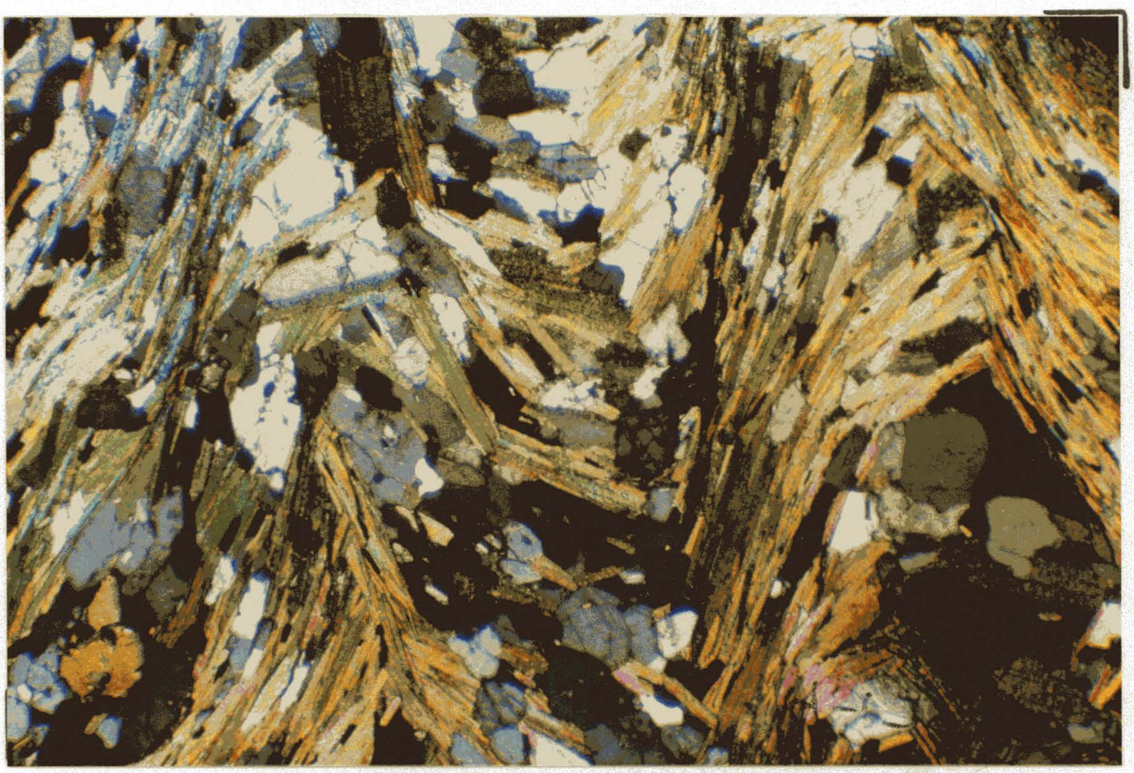


Plate 3b. Sample 4-177-e, crossed polars.

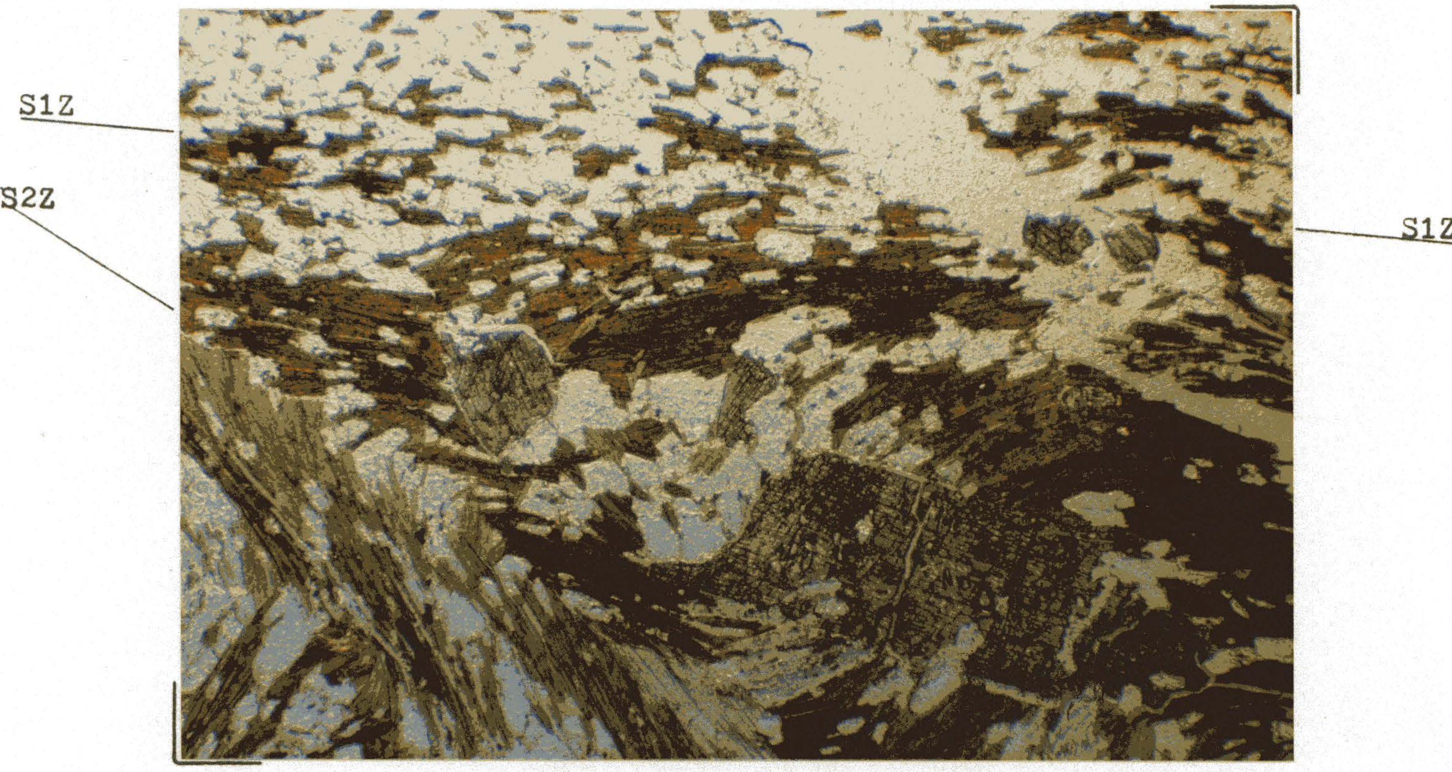


Plate 4a. Sample 4-178-e, plane light. Post S1Z pre-S2Z kyanite with quartz inclusion trails at sharp angles to microfolded S1Z fabric. Note quartz-rich Q-domains and mica-rich M-domains parallel to S1Z in upper-half of photomicrograph.

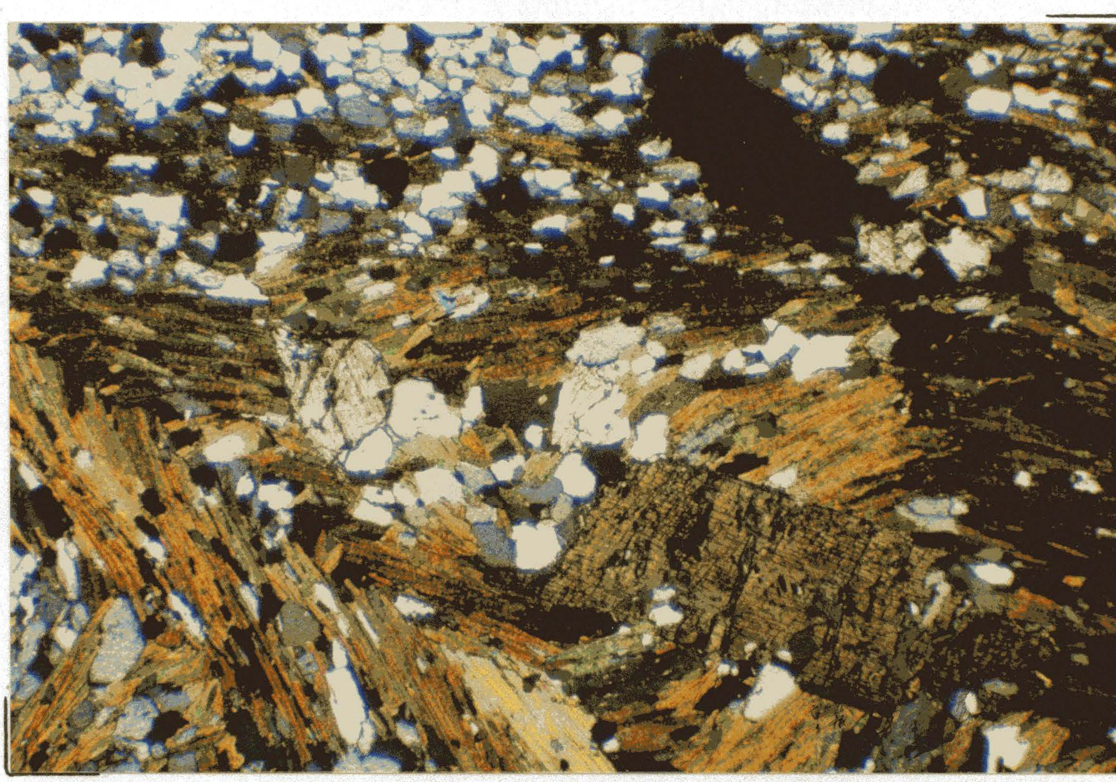


Plate 4b. Sample 4-178-e, crossed polars.

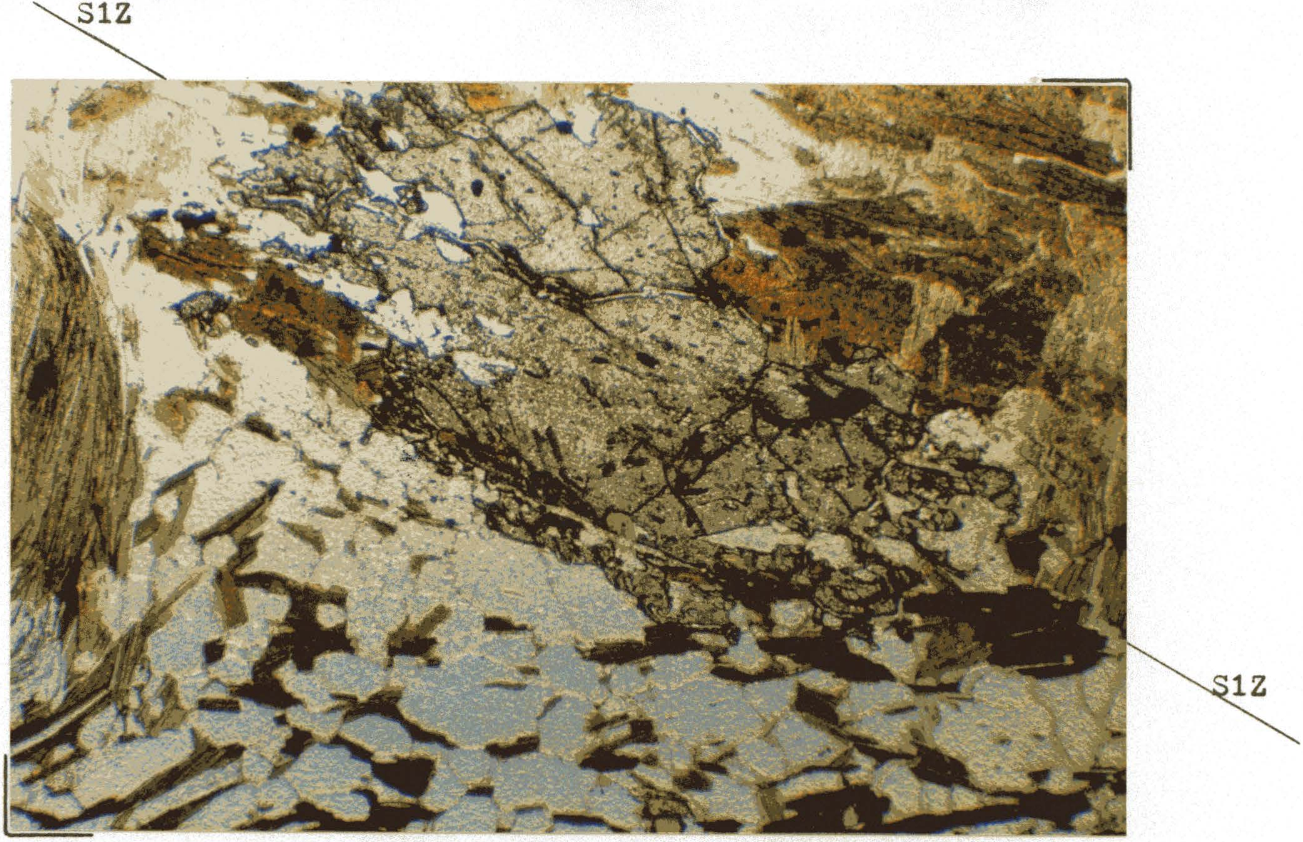


Plate 4c. Sample 4-178-e, plane light. Garnet with Si parallel and continuous with Se (S1Z). Garnet elongate parallel to S1Z (late S1Z?).

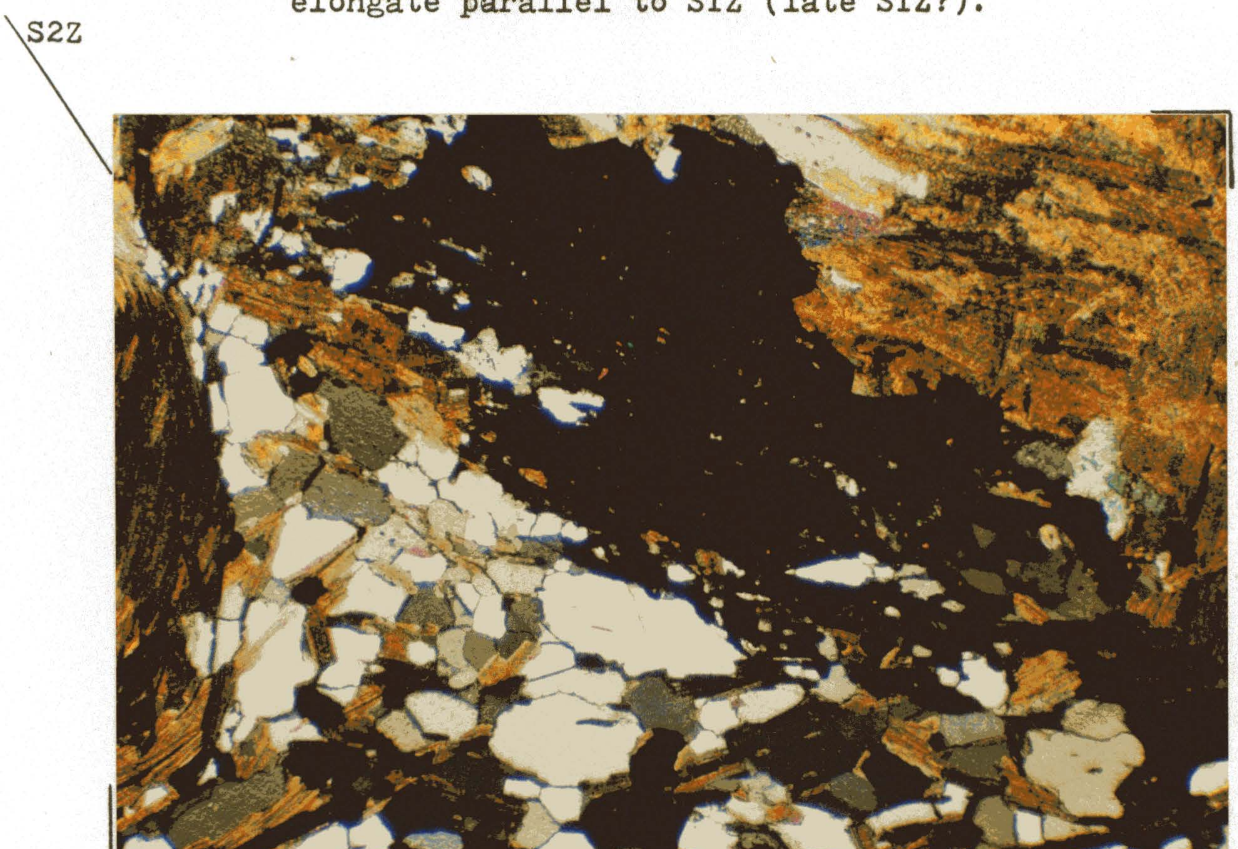


Plate 4d. Sample 4-178-e, crossed polars. Note S2Z defined by axial plane of microfolded S1Z.

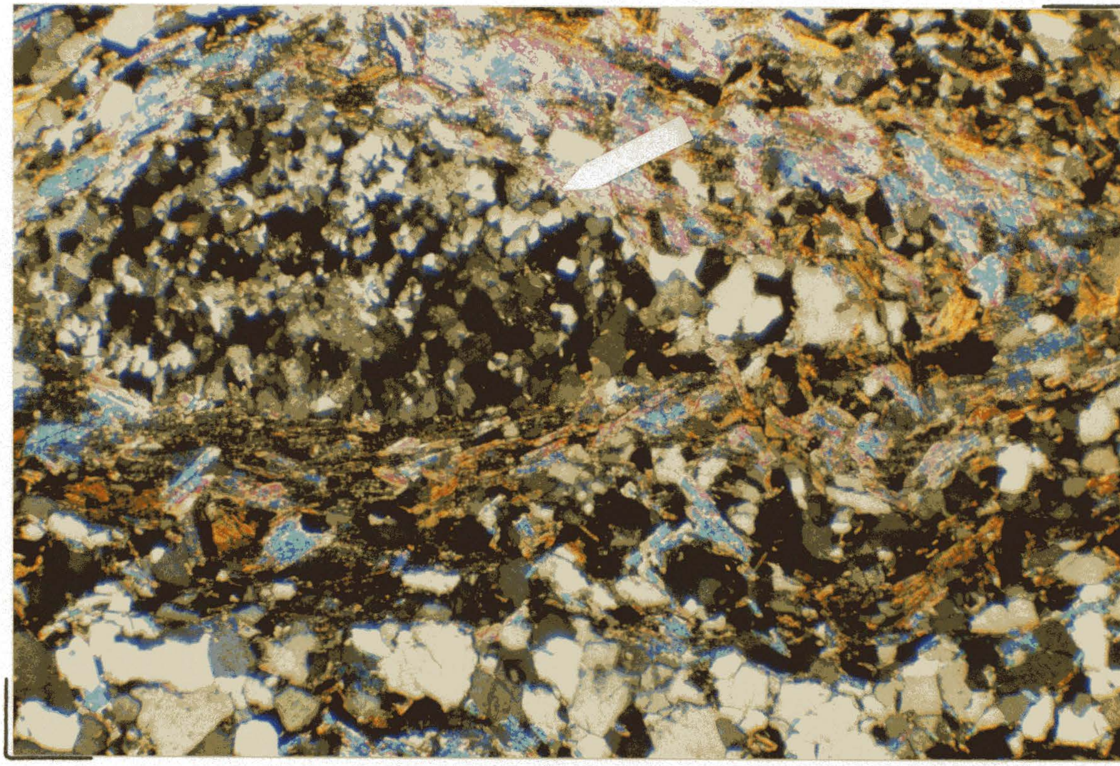


Plate 5. Sample 4-179-e, crossed polars. Arrow marks dynamically recrystallized feldspar augen. Note somewhat systematic orientations of mica overgrowths oblique to S1Z (S1Z is roughly parallel to horizontal axis of photomicrograph).

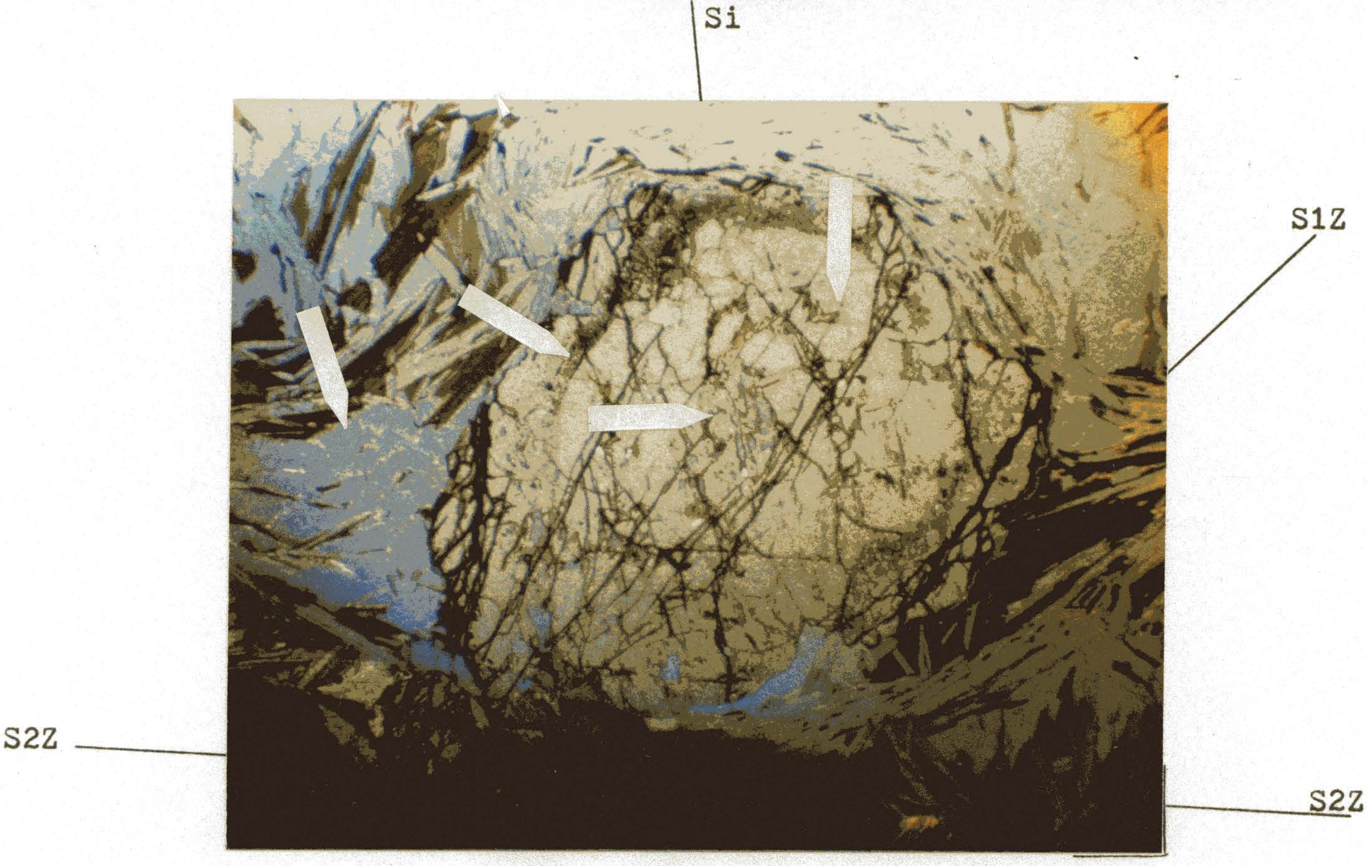


Plate 6a. Sample 4-150-e, plane light. Garnet porphyroblast. Arrows mark 1) S1Z pressure shadow; 2)inclusion-rich inner core; 3) inclusion-poor outer core; 4) dusty band. Note truncation of dusty bands at lower right.

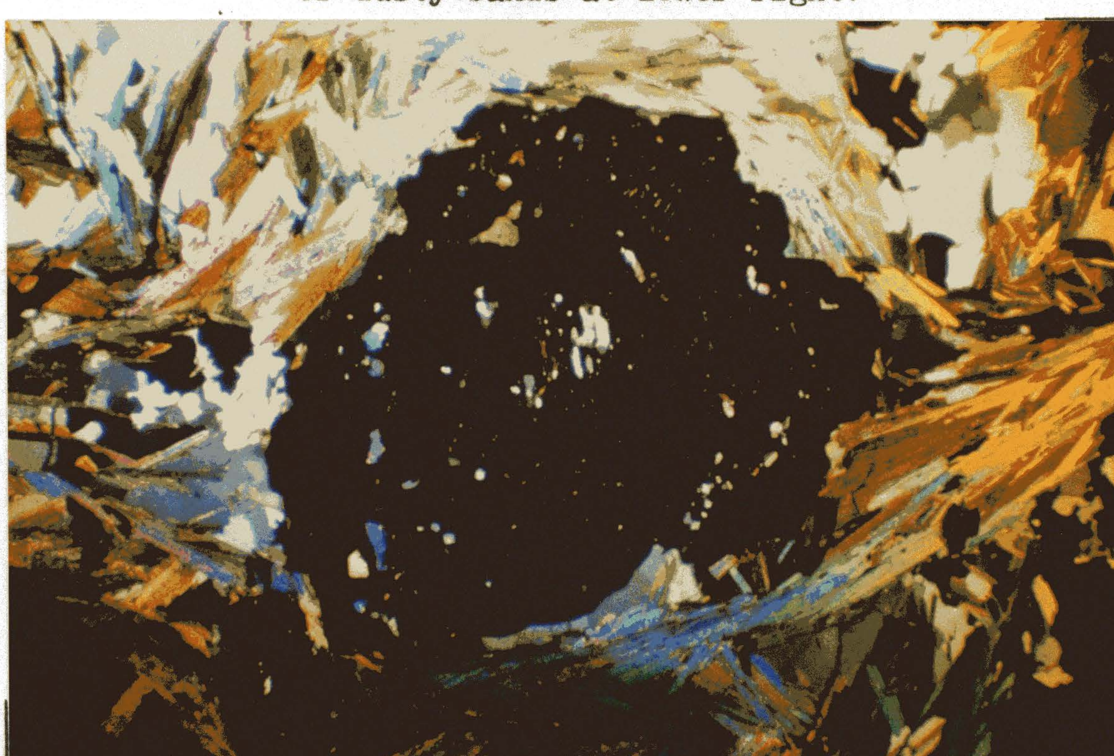


Plate 6b. Sample 4-150-e, crossed polars.

Plate 7a. Sample 4-143-e, crossed polars. Arrow marks pre-S1Z muscovite 'fish'. S1Z parallel to top and bottom edges of photomicrograph.

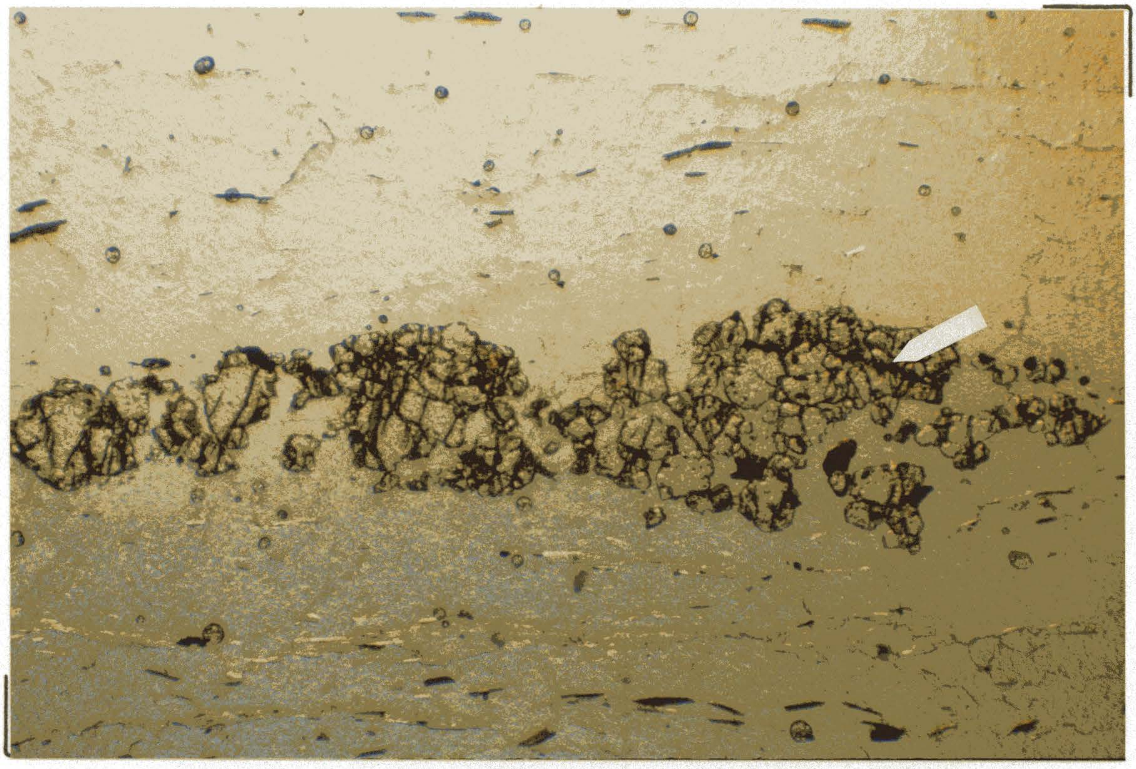


Plate 7b. Sample 4-143-e, plane light. Augen-shaped aggregate of garnet elongate parallel to S1Z. Arrow marks opaque inclusion trail that roughly parallels S1Z.

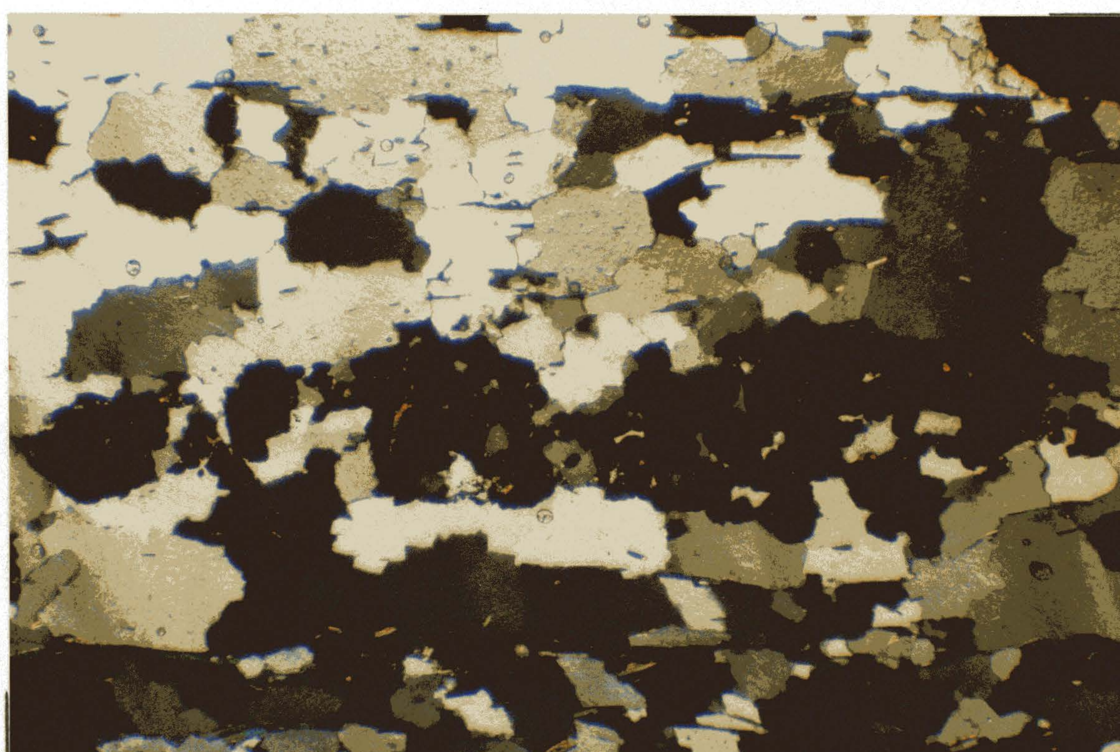


Plate 7c. Sample 4-143-e, crossed polars. Note slight wrapping of garnet aggregate by S1Z.

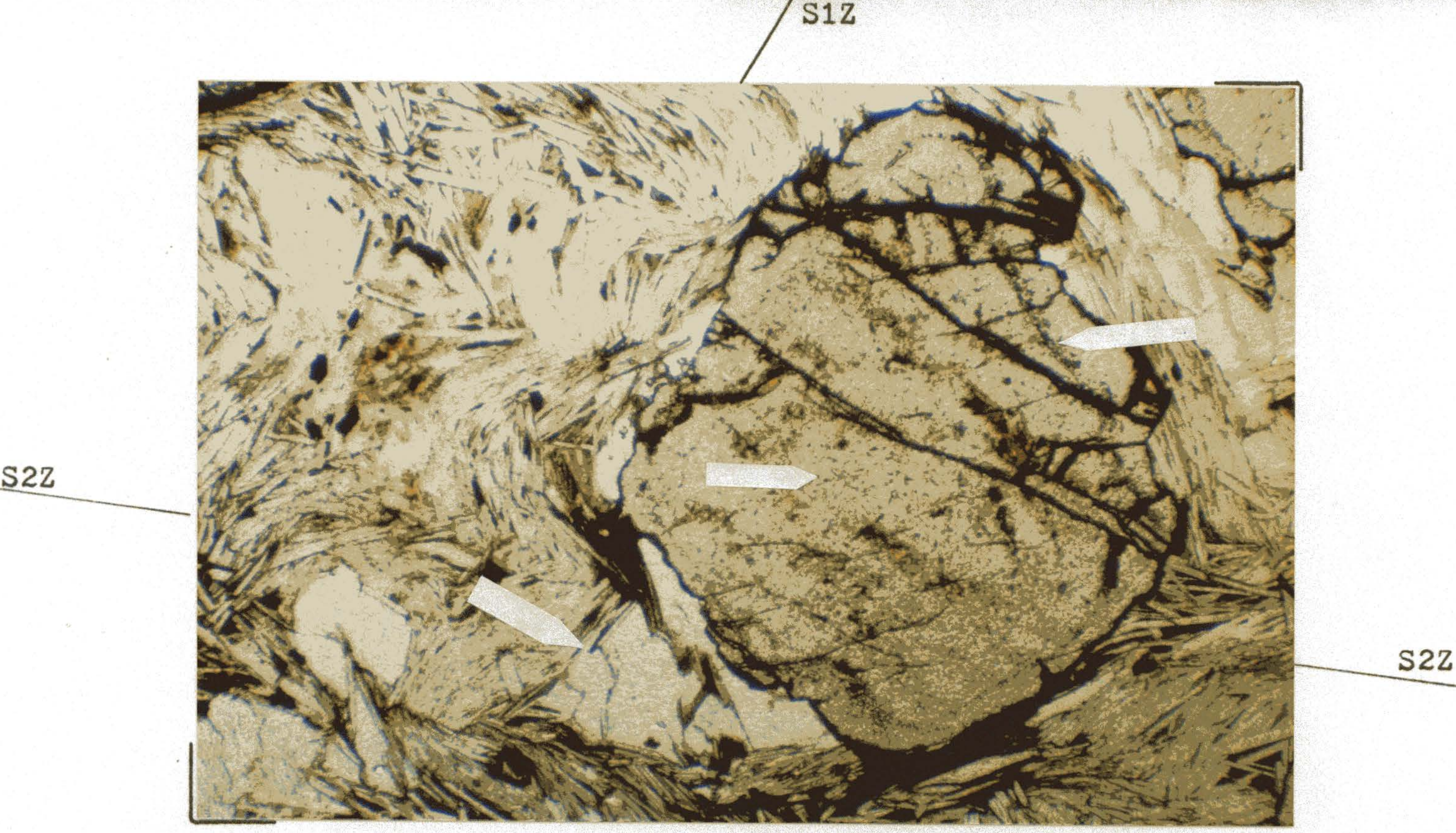


Plate 8a. Sample 4-142-e, plane light. Pre-S1Z garnet porphyroblast. Arrows mark 1) S1Z pressure shadow; 2) dusty band; 3) inner core (inclusions unresolvable).

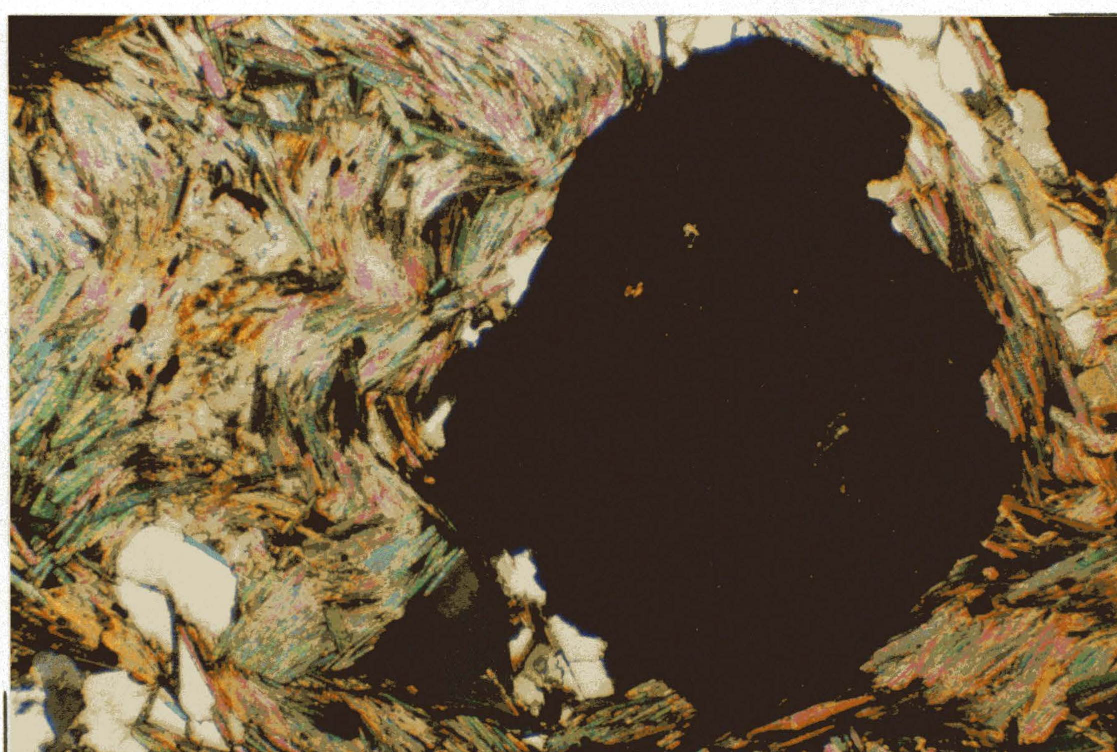


Plate 8b. Sample 4-142-e, crossed polars.

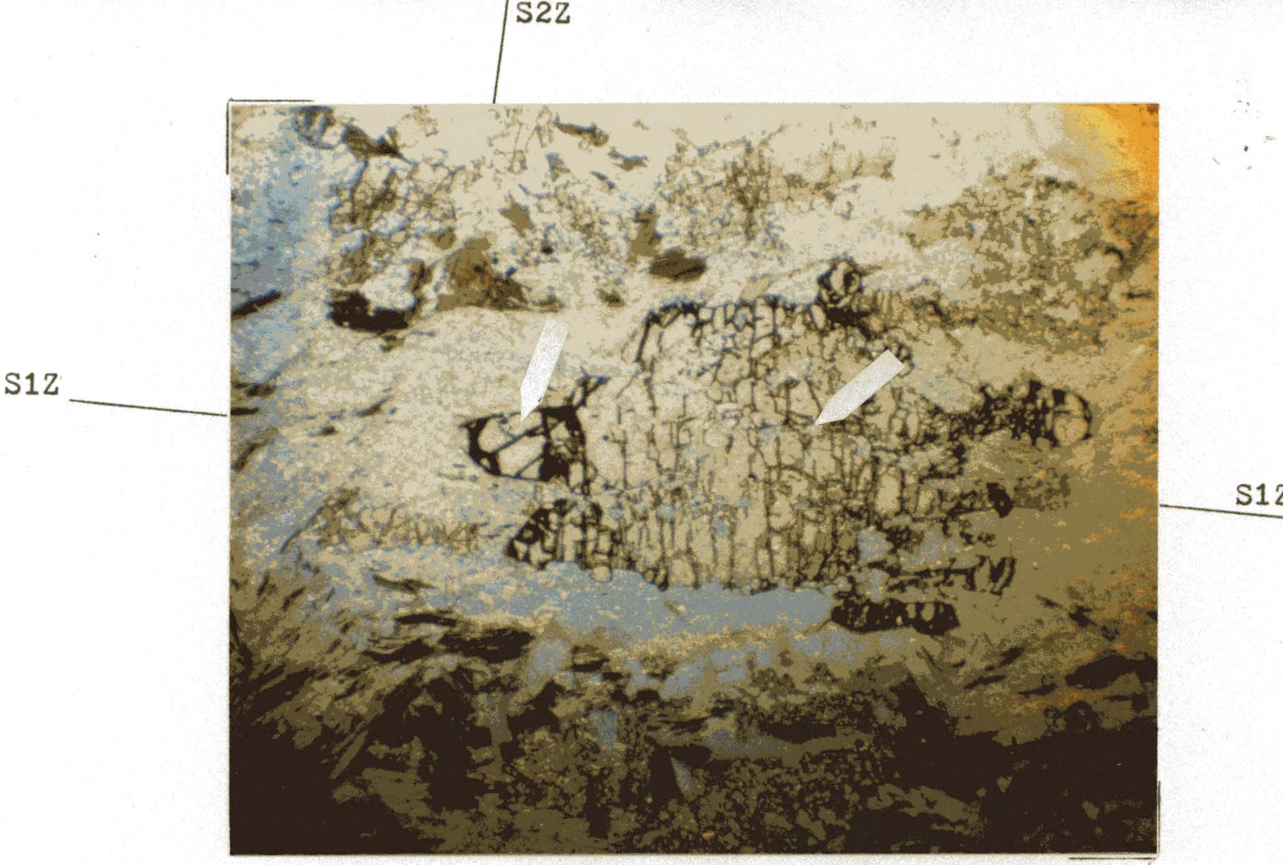


Plate 9a. Sample 4-140-e, plane light. Garnet with inclusion-rich core and inclusion-poor rims. Arrows mark 1) inclusion-free euhedral rims; and 2) inclusion-rich core with curved Si.

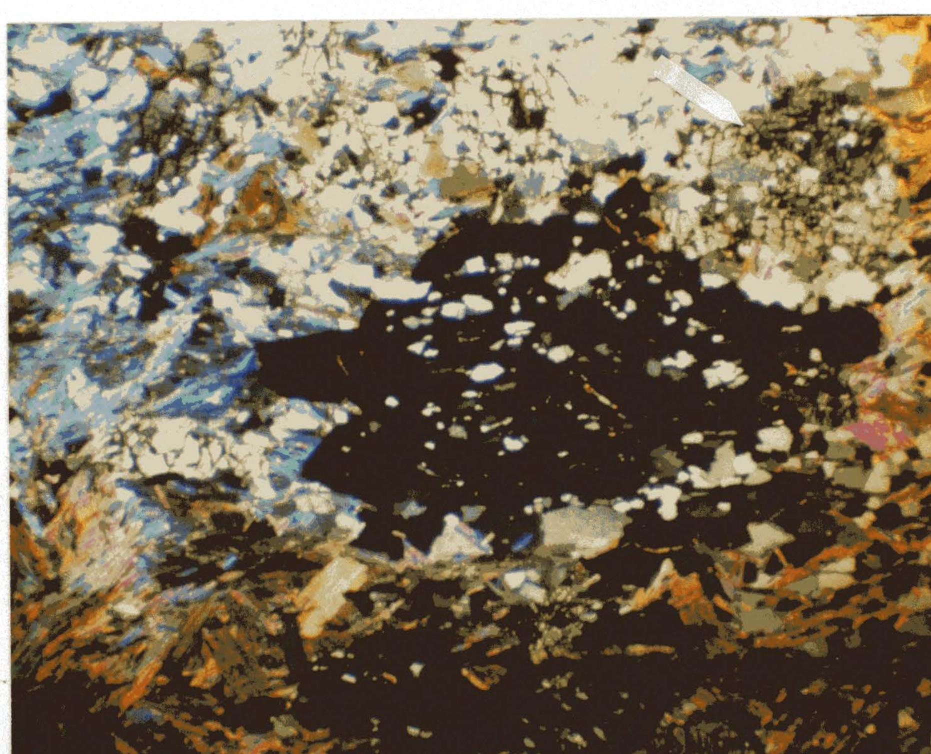


Plate 9b. Sample 4-140-e, crossed polars.

Plate 10a. Sample 4-139-e, plane light. Pre-S1Z muscovite (top) and feldspar (bottom). S1Z parallel to horizontal axis of photomicrograph.

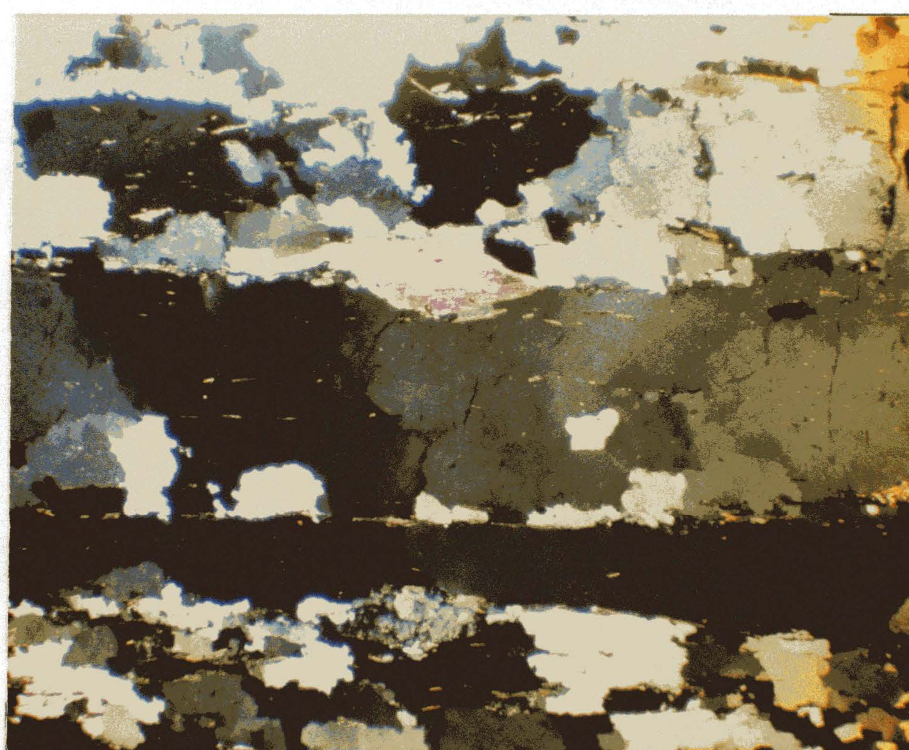


Plate 10b. Sample139-e, crossed polars. Note the wrapping of the muscovite and feldspar porphyroblasts by S1Z.

DISCUSSION and CONCLUSIONS

BASEMENT OR COVER?

Field observations along the Ngonga River traverse revealed no mesoscopic evidence for an earlier, pre-Zambezi fabric, whereas exposures of the same lithologic units along the Mutama River did display older northeast trending fabrics (SI) that had been refolded and crosscut by younger, west-northwest trending Zambezi foliations. This suggests that these older schist units are remobilized Kibaran metasediments initially deformed during Irumide orogenesis. Since the Ngonga River schists contained no obvservable pre-Zambezi mesoscopic fabrics, field correlation of these units with the Mutama River schist units could only be made on the basis of lithologic similarities and location along Zambezi strike.

Microstructural analysis of garnet porphyroblasts within the 'presumed' Kibaran Schists collected along the Ngonga traverse did, however, reveal evidence for pre-Zambezi structural fabrics. Samples 4-150, 4-142b and 4-142 (Fig. 8,Table 1) all contain inclusion-rich garnet porphyroblasts that are of pre-Zambezi age and that appear to preserve an earlier structural fabric, presumably SI. Assignment of a pre-Zambezi age to these garnets was based on both internal and external criterion. The garnets typically 1) were cracked perpendicularly to S1Z; 2) were bounded by apparent pressure shadows oriented parallel to S1Z; and 3) contained inclusion trails of quartz and opaques oriented obliquely to S1Z at different angles in each porphyroblast; all suggesting pre-Zambezi age.

A few garnet porphyroblasts displayed apparent dissolution flattening parallel to S1Z in which internal structures were truncated by the dissolution margin, thus supporting pre-Zambezi age. The garnets were typically zoned, displaying three to five growth stages. The different zones were defined by inclusion-rich and inclusion-poor core zones and by rim zones containing concentric inclusion trails of opaques and quartz that were separated from the inner zones by distinct dusty bands. The relatively inclusion-free zones are considered to represent slow crystal growth and the inclusion-rich zones are considered to be indicative of rapid crystal growth. Since garnet is a metamorphic mineral, the inclusion trails within these garnets must preserve an earlier structural fabric that, presumably, was formed by Irumide deformation and metamorphism. Therefore, it is considered that these samples are remobilized Mutama 'basement complex'.

Samples 4-143, 4-140 and 4-139 contained no pre-S1Z garnets. Sample 4-143 and 4-139 are quartz rich mylonites. Sample 4-143 contains a few augen-shaped aggregates of garnets suggesting that they are of pre-S1Z age, but also contains garnets with opaque inclusion trails that parallel S1Z. Together, the pre- and syntectonic characteristics suggest that these garnets were likely formed during the early stages of Zambezi deformation. Sample 4-139 contains no garnet or any other pre-S1Z porphyroblast with a preserved internal fabric. It is likely that mylonitisation would have removed most, if not all, pre-S1Z porphyroblasts that may have been present in these samples. Sample 4-140 is very similar in composition to 4-150 and was therefore expected to contain evidence for pre-S1Z fabrics within its porphyroblasts, but was observed to contain only syn to post S2Z garnets. The fact that sample 4-140 was collected adjacent to a band of mylonite immediately to the south suggests that, as in samples 4-143 and 4-139, any pre-S1Z garnets would likely have been removed due to the increased flow of metamorphic fluids associated with mylonitisation nearby. These three samples, then, are considered to represent nearly completely transposed Kibaran basement.

The field observations of Hanson and Wilson by which the above six samples were inferred to be remobilized Kibaran 'basement complex' are well supported by the microstructural criterion discussed above. This allows for a more definite correlation between the Ngonga and Mutama River schists.

Katangan Schists collected along the Ngonga River showed no meso- or microscopic evidence of a pre-Zambezi fabric (Fig. 8,Table 1, samples: 4-175, 176,177,178,179). These samples contain a primary S1Z schistosity that, with the exception of 4-176-a, is microfolded by a pervasive S2Z crenulation cleavage. Sample 4-176-a is a fine-grained quartzite (approx. 95%quartz) and is therefore presumed to have been resistant to the second stage of Zambezi deformation. Pre-Zambezi feldspar within these samples is considered to have originated from protolith material and therefore offers no evidence of pre-Zambezi deformation. Many of the Katangan samples also contain garnet porphyroblasts, but no pre-S1Z Si fabrics are preserved within them. The absence of an earlier structural fabric within these rocks indicates that they are transposed Chilumbwe 'cover' metasediments that were deformed and metamorphosed only during Zambezi orogenesis.

SYNCHRONEITY OF DEFORMATION AND METAMORPHISM

The relations between the various stages of metamorphism and the two stages of Zambezi deformation are expressed differently in the Katangan and Kibaran Schists (Table 1). The first stage of Zambezi orogenesis involved deformation and metamorphism of the Katangan Schists to produce an S1Z schistosity defined, generally, by quartz, muscovite, biotite, garnet, staurolite and feldspar. S1Z within the Kibaran Schists is defined, primarily, by the formation of only quartz, muscovite and biotite, with some feldspar and garnet in the two northernmost Kibaran samples (4-143 and 4-150). This appears to indicate an increase in D1Z metamorphic grade northwards towards the central axis of the Zambezi belt, as one would expect.

There is evidence of late to post S1Z, pre-S2Z metamorphism within the Katangan Schists but virtually no evidence for this event in the Kibaran schists. Late to post S1Z, pre-S2Z minerals in the Katangan Schists include muscovite, garnet, feldspar, kyanite and possibly staurolite. This indicates post-D1Z heating to the kyanite or staurolite grade within the Katangan units (Ehlers et al, 1982). Since the Kibaran schists are unaffected by this post-D1Z heating, it is evident that this event was concentrated to the north of the Kibaran units, which suggests that this event was possibly a continuation of D1Z metamorphic processes discussed above.

The second stage of Zambezi deformation coincided with metamorphism that was apparently of higher grade in the Kibaran Schists. All of the Kibaran Schists, with the exception of the quartz mylonites (4-139 and 4-143), contain syn-S2Z crystals of muscovite and biotite with syn-S2Z garnet and possibly staurolite in sample 4-140. Only one of the Katangan Schist samples (4-177) contains S2Z crystals of muscovite and biotite that are undoubtedly associated with D2Z. The principal evidence of D2Z within the Katangan Schists is limited only to microfolding of S1Z fabrics, with little recrystallization. This appears to indicate an increase in metamorphic trend to the south during D2Z, which is the reverse of the apparent metamorphic grade during D1Z.

Post D2Z metamorphism is minimal throughout the Ngonga traverse, with some post S2Z muscovite and possibly garnet occurring in three of the eleven samples analyzed. This post-D2Z event is considered insignificant relative to the samples discussed.

The SI garnets within the Kibaran Schist cannot be analyzed optically to determine detailed evidence for metamorphic grade and timing. For future research, electron microprobe analysis of the chemestry of each of the garnet zones and dating of any zircon inclusions etc., may reveal a more complete understanding of Irumide orogenesis in the Ngonga region.

A MODEL FOR P-T PROGRESSION THROUGH TIME ALONG THE SOUTHERN ZAMBEZI BELT MARGIN

The first stage of Zambezi deformation appears to have coincided with medium amphibolite grade metamorphism of the Katangan units and lower grade, possibly epidote-amphibolite or greenschist facies, metamorphism of the Kibaran units, as evidenced by the mineral-fabric relations discussed above. In the sense of regional tectonics, this trend of increasing metamorphic grade to the north suggests that the Katangan units were likely at a deeper crustal level during D1Z and were subsequently uplifted during progressive tectonism. This supports the suggestion of Wilson et al. (1985) that southward directed thrusting occurred along the Zambezi/Irumide junction. South-directed thrusting would uplift the Katangan Schists relative to the Kibaran units through time.

Assuming north-over-south thrusting, a possible explanation for the post D1Z, pre-D2Z mineral growth relations in the Katangan Schists could be heating of the Katangan unit due to plutonism associated with deep crustal melting of Irumide basement as it was underthrust beneath the Katangan Schists (Spear et al.,1984). This could also explain why little to no post-D1Z, pre-D2Z mineral growth occurred southward in the Kibaran Schists, as they would not be affected by injection of the crustal melts. The evidence for higher grade D2Z metamorphism in the Kibaran units could also be explained by this model. During D2Z, the hotter Katangan units to the north were progressively overriding the Kibaran units to the south. This created a metamorphic regime in which the cooler, underthrusted Kibaran crust was heated by the hotter, overriding Katangan crust which would be cooled by this structural uplift.

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